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NBSEH aims to advance knowledge, foster interdisciplinary dialogue, and promote innovative solutions for a healthier, more sustainable, and more resilient world.

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Faculty of Science and Technology Mohammedia
Hassan II University of Casablanca
BP 146, 28806 Mohammedia Morocco

amstesmaroc@amstes.org

www.amstes.org | www.nbseh.org

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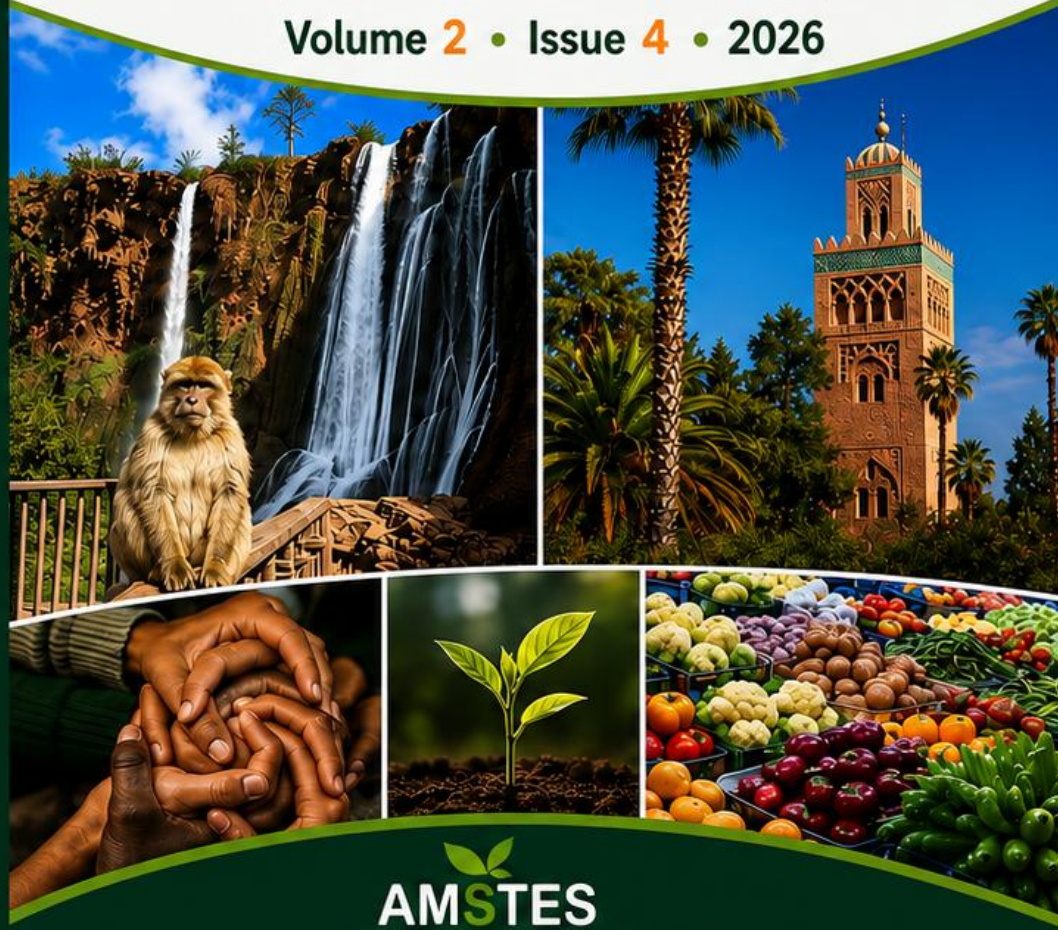

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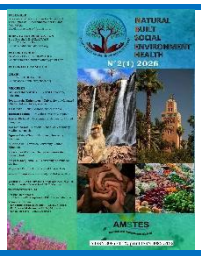

Living Soil Museums in Ukraine: A New Platform for Soil Literacy, Citizen Science and Community Engagement

Dmytruk Yuriy [1,2,a*], Cherlinka Vasyl [1,3,b]

[1] *Society of Soil Experts and Land Managers of Bukovyna 'Terra', Chernivtsi, Ukraine*

[2] *HEI Podillia State University, Kamianets-Podilskyi, Ukraine*

[3] *Research and Solutions, Mississauga, Ontario, Canada*

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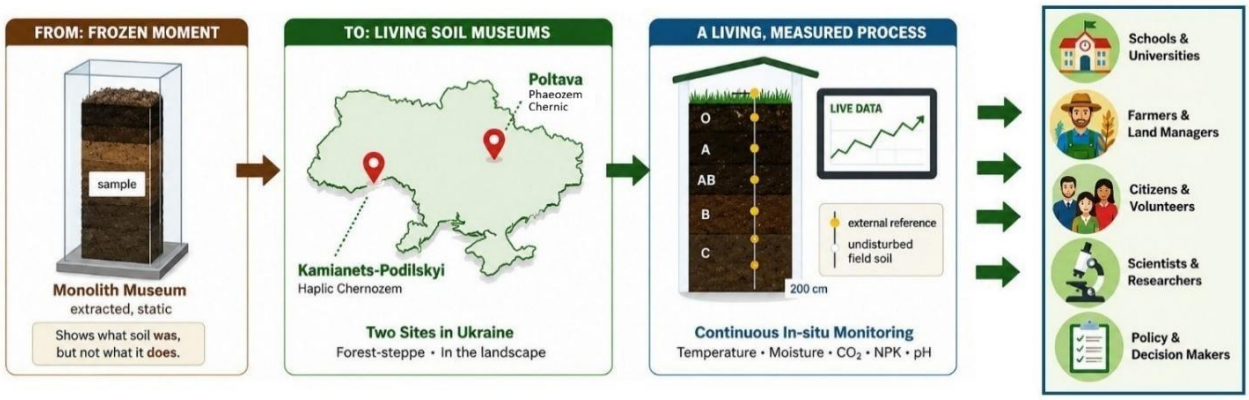
[a] **ORCID:** 0000-0002-3157-0503 ; ***Email***: *y.dmytruk@pdatu.edu.ua*

[b] **ORCID:** 0000-0001-5354-4851 ; ***Email***: *vasyl.cherlinka@research-solutions.ca*

Corresponding author:* Dmytruk Yuriy; ***Email*: *yuriy.dmytruk@terra-ukraine.org; y.dmytruk@pdatu.edu.ua*

Graphical abstract

Traditional soil museums that display only preserved soil monoliths cannot communicate what soil health actually means, because a preserved sample cannot show a living system. Here we describe the establishment of two Living Soil Museums in Ukraine built around undisturbed soils in their natural setting, created under the Horizon Europe SoilTribes project. As more such museums appear, there will be increasing value in common approaches for documenting their activities and comparing their educational and scientific performance.



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Abstract: Soil remains one of the least visible and least understood natural resources; even as European and global policy frames soil health as a key to food security, climate resilience and biodiversity. Traditional soil museums, built around preserved soil monoliths, cannot communicate what soil health actually means because a preserved sample cannot show an alive and actively changing system. This article describes the establishment of two Living Soil Museums in Ukraine—in Poltava and Kamianets-Podilskyi—developed under the Horizon Europe SoilTribes project. These living exhibits keep an undisturbed soil profile in its natural state in the landscape and install continuous sensors for temperature, moisture, reaction and other parameters, visualized for visitors in near real time. The discussion embraces the aims, design, construction and sensor architecture of the living museums and their emerging role as platforms for citizen science for schools, farmers, volunteers and the wider public in the context of the European Union's mission A Soil Deal for Europe. Living soil museums by no means replace conventional soil collections but offer a replicable model for deeper public engagement with our soils.

Keywords*: Living soil museum, Soil literacy, Ukraine.*

Introduction

Soil sustains 95 per cent of global food production [1], hosts at least a quarter of biodiversity [2], and regulates water, carbon and nutrient cycles at every scale from a single field to the whole Earth system [3]. But it is largely invisible and intangible. We can watch and feel a river changing, smell and taste polluted air; but the biological and chemical processes that determine whether a soil is healthy happen below the surface, sometimes on timescales and at depths beyond ordinary perception. Invisibility means that people find it hard to appreciate, value and, therefore, to demand protection for soil. Both European and global policy have converged on the view that this communication gap has practical consequences. The European Union's Horizon Europe Mission: '*A Soil Deal for Europe*' (or *Mission Soil*) sets an explicit target of 75 per cent of EU soils to be healthy by 2030, which means doubling the current baseline [4,5]. The Mission's own implementation documents identify *soil literacy*—public understanding of what soil is and does—as a precondition for reaching that target, alongside research, monitoring and on-the-ground demonstration through '*Living Labs'* and '*Lighthouses*' [6]. FAO has also pursued a parallel, longer-running initiative to build public and political awareness of soil as an irreplaceable but vulnerable resource [7].

Within environmental psychology and communication, a lack of direct physical visibility and tangible immediacy is recognized as a major barrier to perception and understanding, rendering subterranean or slow-onset ecological threats psychologically distant and largely unappreciated [8]. Vital soil processes are hidden beneath the surface; their chronic depletion is overlooked by policymakers and society until catastrophic ecological thresholds are crossed [3].

Museums are one of the oldest institutional resources to make something that is otherwise inaccessible available for direct public encounter. Soil museums have existed since the late nineteenth century; but what has rarely been attempted is to create a museum around a live soil and its continuously observed processes and functions—not merely a display but a fulcrum for citizen participation in soil science. This is the aim of the first two installations of this kind established in Ukraine (in Poltava and in Kamianets-Podilskyi) and, here, we discuss our early experience.

Strengths and shortcomings of traditional soil museums: Soil museums built around monoliths**—**soil blocks excavated, dried or resin-stabilized**—**remain invaluable. Institutions such as the ISRIC World Soil Museum, in Wageningen, hold extensive reference collections that allow direct comparison of soil types from across the world and, indeed, retain profiles that may no longer exist in the field because of land-use change. Several national soil museums of this kind, including

legacy collections from the nineteenth century, have played a comparable role in preserving representative specimens for teaching and taxonomic reference.

Table 1. Traditional soil monolith museums compared to living soil museums

Feature	Traditional monolith museum	Living Soil Museum
Physical basis	Extracted, stabilized soil block	Undisturbed profile in its natural position in the landscape
Temporal character	Fixed at the moment of sampling	Continuously changing; observed over time
Biological / physical activity	Absent (removed by extraction and stabilization)	Present and monitored (gas exchange, moisture regime, biotic activity)
Data shown to visitors	Static labels. Field profile descriptions and standard analytical data may be available	Real-time and historical sensor data on a dashboard
Interactivity	Mostly observational	Visitors can query live data; some volunteer / verification activities possible
Maintenance needs	Low (conservation only)	Higher (sensors, connectivity, calibration)
Primary strength	Cross-regional comparison; taxonomic and historical reference	Demonstrating soil as a living, functioning system *in situ*
Primary limitation	Cannot show dynamic processes	Cannot easily be relocated or compared side-by-side to other soil types on one site

The strengths of this format are real. A monolith enables direct visual and tactile inspection of horizon sequences, requires no power supply or maintenance beyond basic conservation, and can be transported or loaned between institutions. It is unmatched for showing what a given soil profile looked like at the time of sampling. Its limitations follow directly from the same physical fact: a monolith is fixed at the moment of excavation. It cannot show soil water responding to a rain event, heat moving through a seasonal cycle, or biological activity varying with the weather and management, because the act of extracting and stabilizing the block removes it from the very physical and biological environment that drives these processes. Three specific consequences follow. First, *static display:* whatever the exhibit shows is one instant, not a process, so it cannot communicate the concept of soil health—a capacity of soil to function over time [9,10]. Secondly, *no real-time observation:* visitors cannot see a soil property or process change before their eyes, which removes the most persuasive demonstration available to any exhibit of a living system.

Thirdly, *limited interaction:* most monolith displays are viewed rather than engaged with, whether by comparing a live reading, making a measurement, or seeing one's own observation reflected back.

This is not a criticism of monolith collections; they answer questions different from the communication of soil health that now needs attention and which we are trying to illustrate with a living, monitored soil individual (Table 1).

Development of the first Living Soil Museums in Ukraine

Design philosophy and construction

Our first two installations were developed under the Horizon Europe SoilTribes project which supports soil literacy and knowledge co-creation [11]. The concept is that the soil profile, itself, should remain an actual, undisturbed part of the landscape rather than becoming an inert specimen. In practice, this meant excavating a space considerably larger than a conventional soil pit, both to admit visitors for *in-situ* observation and to house monitoring equipment. The resulting excavations measure 2×10m at the Kamianets-Podilskyi site and 3×8m at the Poltava site, both to a depth of 2m. At both sites the perimeter profile wall was left in place, physically continuous with the surrounding landscape so that lateral water movement and biological activity can continue much as they would in undisturbed soil.

a **b**

Figure 1. Protective polycarbonate structure over the exposed soil profile on Poltava site: **a** - outside, **b** - inside **.**

Figure 2. Specific windows are provided to enable visitors' direct interaction with living soil

Figure 3. Interior of the shelter, featuring a perimeter ventilation gap and a glazed floor section for observing the parent material

To protect the exposed walls from the elements and to prevent collapse or erosion, a shelter was built over each excavation. At Poltava, a custom-built structure roofs the museum area with polycarbonate sheeting (Figure 1a, 1b); the soil walls are enclosed with double-glazed panels, several of which can be opened to give visitors direct contact (Figure 2). A 10cm gap runs along the perimeter of the structure to maintain air exchange with the surroundings. The floor is wood-decked except for one glazed section which reveals the parent material underfoot as well as on the profile wall (Figure 3).

Figure 4. Prefabricated polycarbonate shelter at the Kamianets-Podilskyi site: **a-** ventilation windows for natural air exchange; **b-** overview of the museum entrance

At Kamianets-Podilskyi, a prefabricated structure (Figure 4a) was mounted on a surface-level foundation without excavating along the museum perimeter; its roof and walls are both

polycarbonate, and windows provide ventilation (Figure 4b). The floor is, likewise, wood-decked and stairs give access to the museum interior (Figure 5). At present, the profile walls at the Kamianets-Podilskyi site remain exposed to the air, without any glazing; the site is being monitored and glazed panels will be fitted, as at Poltava, should there be any deterioration.

Figure 5. Wooden stairs and unobstructed soil profile wall sections

At both sites, one section of the profile wall is kept unobstructed to accommodate the sensors used for continuous soil monitoring (Figure 6). These sensors are emplaced in the profile at the time of construction and because the profile is not subsequently reopened; this is also the only stage at which there is physical access to its interior—day-to-day operation depends entirely on these embedded sensors (described below under Making Soil Visible). Both shelter designs maintain air exchange with the surrounding atmosphere and lateral exchange of matter and energy with the surrounding landscape, although, inevitably, the roof intercepts radial (vertical) fluxes through the soil body.

Figure 6. The opposite-to-stairs wall equipped with a sensor panel for monitoring

Poltava site: The Poltava installation, hosted by Poltava State Agrarian University (Figure 7) with the involvement of the NGO Terra, was officially opened on 17 June 2026 (Figure 8). The soil is classified as a Chernic Phaeozem (Siltic) [12] and is broadly representative of the forest-steppe zone of Left-Bank Ukraine.

To ensure optimal comfort and engagement, the capacity of both venues is capped at 15–18 persons. Moreover, aligned with the SoilTribes concept, half of the scheduled activities at each site will integrate cultural and artistic events.

Figure 7. Location map of the sites: 1 - Kamianets-Podilskyi, 2 – Poltava

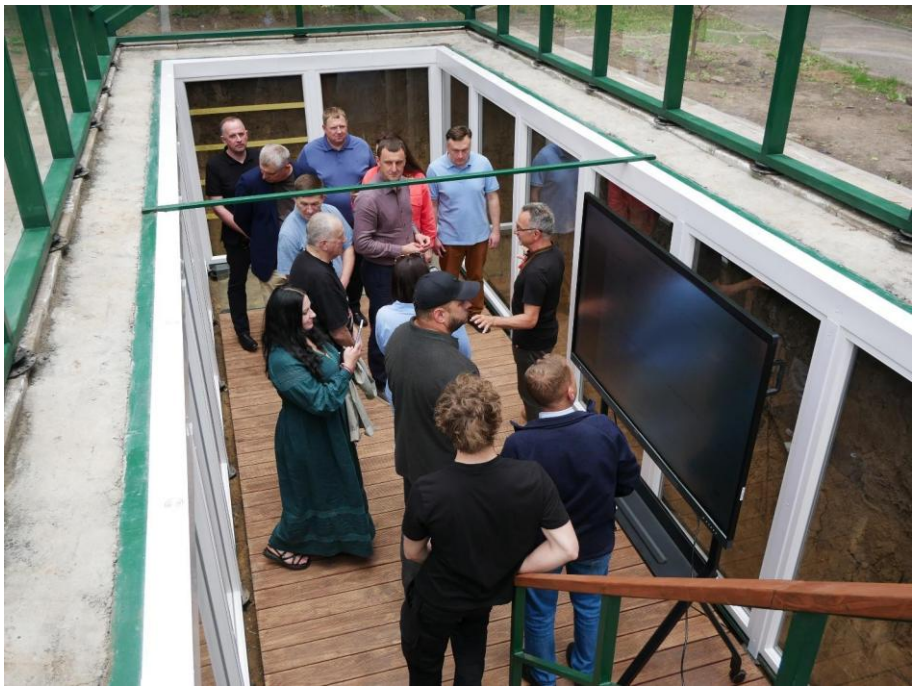

Figure 8. Official opening of the Poltava museum, 17 June 2026

Kamianets-Podilskyi site: The second installation is associated with HEI Podillia State University in Kamianets-Podilskyi (Figure 7). The museum was likewise established with the involvement of the NGO Terra as the operating partner. The soil is a *Haplic Chernozem* (siltic) [12] —a soil type less common in the Western Forest-Steppe but of particular interest as a recognized benchmark soil (Figure 9).

Figure 9. Exposed Haplic Chernozem (Siltic) profile at the Kamianets-Podilskyi museum

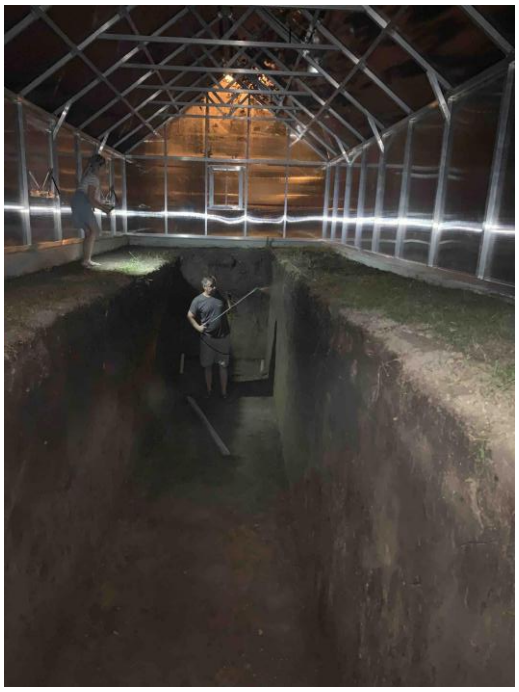

Figure 10. Structural stabilization of the exposed profile wall using a double application of PVA solution

Living Soil Museum as a citizen science springboard

Because a Living Soil Museum maintains an actively monitored, alive soil, it can offer visitors something closer to a genuine scientific task rather than mere explanation. Citizen science in soil monitoring has, over the past decade, grown from a marginal add-on to environmental education into a recognized complement to formal monitoring networks—partly because volunteer observation can achieve an observation density that professional survey campaigns rarely can and, partly, because European soil policy has explicitly recognized that soil health cannot be assessed, or defended politically, by professionals alone [6]. More widely, citizen science has already achieved long-term societal outcomes [13].

The scale of present citizen-science activity concerning soil is, itself, informative for assessing where Living Soil Museums can add value. A 2023 review for the EU Soil Observatory's ECHO project screened 91 soil-related citizen-science initiatives identified through literature searches, project databases, citizen-science platforms and expert outreach via the European Soil Data Centre (ESDAC) network; 71 initiatives were retained for detailed analysis and inclusion in the ECHO repository [14]. Two findings are germane. Firstly, Europe accounted for 66 per cent of identified initiatives, with Africa and South America together accounting for only 3 per cent—meaning that any single new site adds to a sparse global base rather than to an already-saturated one. Secondly,

and more importantly for design purposes, only 13 of the 71 catalogued initiatives involved citizens in genuinely collaborative or co-created roles (contributing to the design or interpretation of the research), as opposed to simple data contribution; partly because of a lack of durable, trusted local infrastructure that can sustain deeper participation [14]. A permanent, staffed installation such as a Living Soil Museum could provide exactly that kind of local infrastructure.

Actual participation

The Living Soil Museum serves not only as an educational facility but also as a permanent Soil Knowledge Hub, integrating scientific evidence, citizen engagement and policy dialogue (Table 2).

At least three kinds of citizen engagement around the two sites are already evident:

School and university groups. The Living Soil Museums were commissioned by the end of June 2026 when Ukrainian schoolchildren and students had already completed the academic year; their involvement in the museums' activities will therefore begin in September 2026. Meetings were held with the rectors of the leading universities in Poltava and Kamianets-Podilskyi to discuss using the museums to strengthen the educational process through practical classes. Similar meetings are planned with secondary-school science teachers, so as to align student excursions to the Living Soil Museums with relevant lesson topics. The museum's dashboard offers a ready-made dataset for basic data-literacy exercises that most schools cannot generate independently, enabling pupils to compare a professionally instrumented reference profile against any measurement they take themselves, whether on a school plot or using a smartphone.

The Living Soil Museum was presented during the Dual Education Forum at Poltava State Agrarian University on 25 June 2026, demonstrating its role as an innovative platform integrating scientific knowledge, artistic interpretation and citizen science. This and other events demonstrate that, as both an exhibition and an experimental environment, the museum provides practical learning opportunities and fosters dialogue between universities, business and local communities. Its integration into educational programmes will strengthen interdisciplinary training and promote sustainable soil management practices.

Table 2. Functional domains and representative activities of a Living Soil Museum

Functional domain	**Representative activities**	**Primary participants**	**Scientific / societal value**
Real-time soil monitoring	Observation of real-time sensor data (soil moisture, temperature, CO_2 concentration, electrical conductivity, *etc.*); interpretation of temporal trends	General public, students, researchers	Makes dynamic soil processes observable; improves soil literacy and understanding of soil functioning
Citizen science	Simplified field measurements, participatory observations, contribution of local environmental data	Schools, community members, NGOs	Encourages public participation and environmental stewardship while improving data literacy
Formal education	Curriculum-linked practical classes, university field exercises, teacher training	Schools, universities	Supports inquiry-based learning and integration of soil science into education
Professional learning	Demonstrations of soil health indicators, workshops for farmers and advisers, interpretation of reference soil profiles	Farmers, consultants, land managers	Promotes adoption of soil health assessment and sustainable management practices
Cultural interpretation of soils	Soil art exhibitions, artist residencies, soil colour palettes, storytelling, exhibitions on soil heritage, performances inspired by soils	Artists, cultural institutions, general public	Connects scientific knowledge with cultural values and emotional engagement, strengthening public appreciation of soils
Community engagement	Public lectures, open days, thematic festivals, volunteer programmes, World Soil Day celebrations	Local communities	Builds long-term relationships between science and society
Historical and environmental memory	Interpretation of paleosols, land-use history, archaeological evidence, post-disturbance soil recovery	Public, students, decision-makers	Demonstrates soils as archives of environmental and cultural history
Climate communication	Demonstration of soil respiration, carbon cycling, greenhouse gas exchange, soil moisture dynamics	Community members, policy stakeholders	Makes climate-related soil processes tangible and understandable
Innovation and digital engagement	Interactive dashboards, augmented reality, mobile applications	Public, young audiences, visitors	Increases accessibility and attractiveness of soil science

Farmer, management and policymaker engagement. For farmers, the opportunity for direct observation of the relationships between soil morphology, biological activity, the water and nutrient cycles may provide a more convincing incentive for voluntary soil health assessment than abstract policy recommendations or regulatory requirements alone. The museum also serves as a science-policy interface where local authorities, land managers and policymakers can understand better how soil functions underpin agricultural productivity, ecosystem services, climate resilience and environmental security. This shared understanding facilitates evidence-based decision-making for land restoration, conservation priorities and investment in nature-based solutions; although the museum should clearly communicate that it demonstrates fundamental soil functions—such as water regulation, carbon cycling, biological activity and buffering capacity—rather than predicting crop-specific fertility or management recommendations for individual fields. Soil function provides the ecological foundation upon which productivity depends, but crop performance remains strongly influenced by local soil variability, climate, management practices and other site-specific factors. Maintaining this distinction is essential to preserve scientific credibility while maximizing the museum's educational and societal value.

Reference-anchored citizen monitoring. The Living Soil Museum can function as a well-characterized reference point within a broader citizen-monitoring framework. Continuously measured parameters relevant to soil health and function are displayed on-site and online, and explained through guided interpretation (scientist-led sessions and interpretive panels), so that visitors learn *to read* the data, not simply view them. Visitors and participating museum-linked partner farms and schools are trained in a standard, low-cost measurement protocol (fixed sampling depth, fixed method and reporting template). Observations collected off-site are submitted through a defined channel (*e.g.*, a simple digital form or the project's Web-GIS portal) and pooled into the baseline soil-monitoring dataset, extending spatial coverage beyond the two museum locations. Obviously, comparability achieved this way applies most directly to soils of similar type and moisture regime to the reference profiles but, beyond their local educational role, both museums are integrated into the broader SoilTribes ecosystem, which provides opportunities for knowledge exchange. Through the project's network of Soil Lab Activators, connecting hundreds of registered stakeholders and dozens of third-party soil-literacy initiatives across multiple European countries, the museums can disseminate educational materials, participate in joint online workshops, webinars and citizen-science campaigns, and share methodological experiences with other Living Labs and soil literacy initiatives [15]. In this way, the museums function as Ukrainian demonstration and knowledge hubs contributing to the European soil-literacy community despite geographical and security constraints. Digital dissemination—including virtual guided tours, live

streaming of soil sensor data, interactive educational modules and open-access training resources—offers a realistic pathway for engaging international audiences while maintaining strong links with local communities.

Making soil visible: Real-time monitoring, interpretation and outlook

Soil monitoring system: What is measured, why it matters and how it works

The concept of a Living Soil Museum is that visitors interact with a living soil rather than static specimens. Each of the two sites carries the same sensor architecture in two co-located configurations: one set embedded in the exhibited profile inside the pavilion, which drives the live visitor-facing display; and a second, equivalent set installed in undisturbed soil immediately outside the pavilion, which provides a field reference unaffected by the enclosed exposition environment. Both configurations monitor soil temperature at multiple depths, soil moisture and reaction, with data transmitted to a cloud platform for near real-time display. Several additional parameters including near-surface CO_2 concentration and available nitrogen, phosphorus and potassium, are also measured using lower-cost industrial sensors. At this stage, they are better suited to showing relative trends than to reporting precise, absolute values, but procedures for their calibration and periodic verification against reference laboratory analyses are being progressively refined.

Within the exhibited profile, the sensor suite provides a continuous vertical record from the surface boundary layer to a depth of 2m; the paired external set records the same parameters in undisturbed soil, so that the exposition regime and the undisturbed field regime can be read side by side.

Sensor instrumentation and vertical profiling

Vertical thermistor chain: A vertical chain of 11 digital temperature sensors (DS18B20) records temperature at 0, 20, 40, 60, 80, 100, 120, 140, 160, 180 and 200cm. In the exhibited profile, this chain characterizes the thermal regime of the sheltered exposition and is the parameter best suited to demonstrating temporal dynamics to visitors; the identical chain in the external reference soil captures the undisturbed field temperature profile, so that the two series together let visitors and staff distinguish the exposition environment from the natural soil regime.

Gas and microclimate probe: An SCD41 sensor positioned just below the surface of the exhibited profile (5–10cm) records CO_2 concentration, temperature and relative humidity. In the enclosed pavilion, this CO_2 reading characterizes the near-surface microclimate, influenced by ventilation

and visitor presence, rather than soil respiration in the strict sense; representative measurement of soil respiration requires a chamber (flux) method, planned as a subsequent stage of the project.

Multiplexed physicochemical probe: An integrated 7-in-1 RS485 (Modbus) probe records, at one-minute intervals, macronutrient indices (nitrogen, phosphorus and potassium), pH, electrical conductivity, volumetric water content and soil temperature. A probe of this class is deployed both in the exhibited profile and in the external reference soil. Because industrial sensors of this type carry known, systematic offsets relative to laboratory methods, their readings are treated as indicators of relative dynamics rather than as absolute values. They are being progressively calibrated and verified against reference soil analyses; volumetric water content and electrical conductivity, likewise, require soil-specific calibration and temperature correction for absolute interpretation.

At the surface, a pyranometer (RS485, range 0–2000 W/m², spectral response 400–1100 nm) records incident solar radiation. Although this spectral range extends beyond the strict PAR band (400–700 nm), the sensor serves as a cost-effective proxy for surface PAR estimation after calibration, while providing the necessary radiative context to interpret the site's thermal and moisture regime.

Visualization interface and meteorological integration

All telemetry is visualized on a 65-inch interactive display inside the pavilion. Operating continuously and equipped with motion-activated wake-up sensors, the display hosts a dynamic, bilingual (Ukrainian and English) dashboard that displays real-time data plots, numerical readouts and explanatory contextual annotations.

Off-grid power supply and cloud communication

Each pavilion operates completely off-grid, powered entirely by an independent photovoltaic system consisting of eight flexible solar panels with a combined output of 800W, which continuously charge a portable power station with a capacity of 2.048kWh. Data transmission to the cloud database and the web portal is handled via a 4G LTE cellular router equipped with a dedicated SIM card, removing the need for local Wi-Fi or institutional network access. Data packets are uploaded at 1-minute intervals.

Data pipeline and automation workflow

Data acquisition and visualization are fully automated. The live dashboards deployed on both the public web portal and the pavilion's internal display automatically query the updated database, rendering real-time visualizations.

From number to understanding:

Two design choices determine whether continuous monitoring actually improves a visitor's understanding, as opposed to simply adding a screen to an otherwise conventional exhibit. The first is real-time or near-real-time display: a dashboard inside the exhibition space, updated frequently enough for a returning visitor to notice a change since the previous visit. The second is interpretation rather than raw display: a bare number such as '14°C at 40cm depth' communicates little to a non-specialist visitor without some reference point—a seasonal range, a simple qualitative band, or a comparison with a familiar surface condition—that makes it possible to judge whether the value is unusual, expected, or a sign of something worth discussing with museum staff. Both sites currently emphasize the first of these two design choices (live display) more strongly than the second (interpretive framing); strengthening the interpretive layer is an attractive, low-cost next step.

Future possibilities

The two new Living Soil Museums are initial implementations. Their current configuration demonstrates the feasibility of continuous, *in situ* soil monitoring within a museum environment, but several complementary directions of travel could substantially broaden their scientific and societal value.

From a technological perspective, future development will include remote access to monitoring data, allowing schools, researchers and interested citizens to follow temporal changes from beyond the museum itself. Such expansion would require solutions for long-term data management, quality assurance and digital infrastructure. Equally important is further improvement of data interpretation. Presenting measurements is not enough: future systems should translate sensor observations into understandable explanations of soil processes, ecosystem functioning and climate-related dynamics.

A second direction concerns education and public engagement. Living Soil Museums have the potential to evolve from exhibition spaces into springboards for inquiry-based learning, citizen science and interdisciplinary collaboration. Integration with formal school curricula, teacher

training, community monitoring programmes and cultural or artistic interpretation of soils could strengthen soil literacy while maintaining scientific accuracy.

Finally, as additional Living Soil Museums emerge, there will be increasing value in developing common approaches for documenting their activities and comparing their educational and scientific performance.

These perspectives should be regarded not as commitments, but as realistic pathways through which the Living Soil Museum concept may continue to develop. Like most similarly-funded pilot installations, ours faces a structural mismatch between short project funding cycles and the multi-year institutional commitment that a genuinely long-term monitoring record requires. Neither installation has yet operated long enough to demonstrate how it performs across several full seasonal cycles, let alone across the kind of multi-year record that would let it also serve a research function in its own right.

It is also important to state plainly what a Living Soil Museum is not. It is not a replacement for monolith collections, which retain unmatched value for cross-regional comparison and historical reference, nor is it a substitute for the dense, statistically representative monitoring networks (of the kind operated at EU level through the LUCAS Soil survey and coordinated nationally in many member states) that policy actually depends on for aggregate assessment. Its contribution holds value in another capacity: making the concept of soil function tangible to a visitor at one specific place, in a way that a laboratory report or an aggregated statistic cannot.

The most direct opportunity for future work is replication and comparison: applying a shared, explicit set of design criteria to any future Living Soil Museum, so that new installations can be planned against a known standard rather than each starting from first principles, and so that the two Ukrainian sites can eventually be compared, on equal terms, with any comparable installation built elsewhere.

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Addressing Water Scarcity using Repurposed Oil Carriers

Capt. (Dr.) Nitin Agarwala *

Visiting Lecturer, Naval War College, Verem, Goa, India

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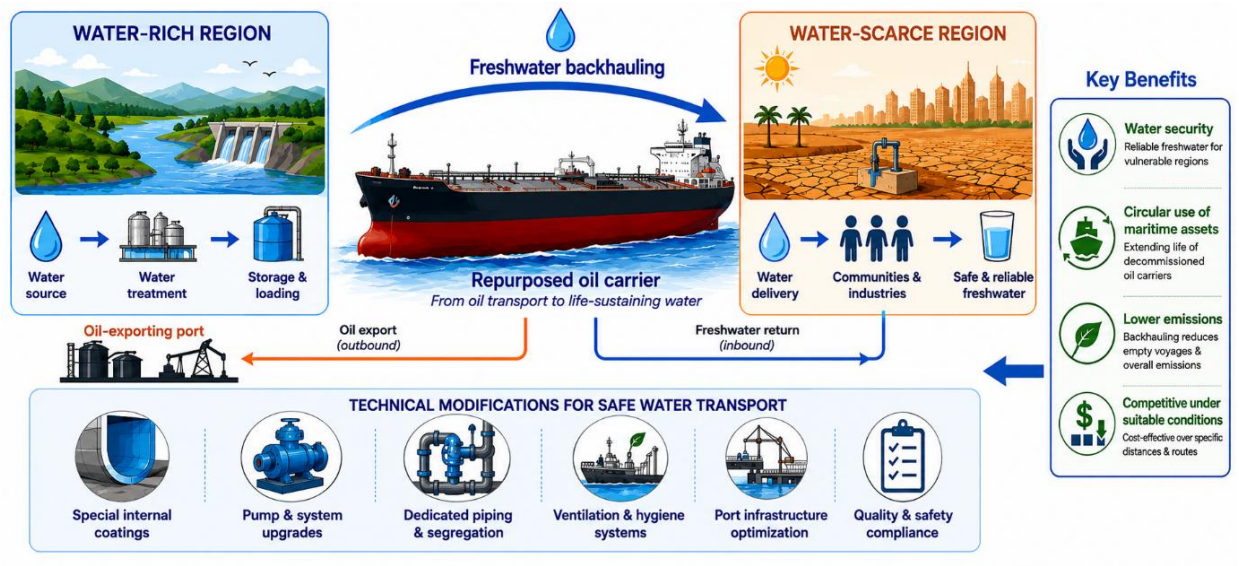
Corresponding author: Capt. (Dr.) Nitin Agarwala ; **Email:** nitindu@yahoo.com

Graphical Abstract

Freshwater scarcity is an increasing global challenge, and repurposing decommissioned oil carriers for freshwater transport could provide a scalable and flexible solution to redistribute water between water-rich and water-scarce regions. This approach requires engineering modifications, dedicated infrastructure, and optimized operational strategies to ensure safe, efficient, and reliable water transport. Economic comparisons with desalination identify the conditions under which maritime freshwater transport becomes competitive, offering a practical framework for strengthening global freshwater resilience.



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Abstract: Freshwater scarcity causes social, economic, political, and environmental unrest. With unequal freshwater distribution globally, trading of freshwater can be a possible solution. But water trade, unlike oil trade, is not a recognized market. It would require a water trading fleet. Repurposed oil carriers as a scalable, flexible solution could be a first step. Engineering modifications, special internal coatings, environmental considerations, and port loading and unloading infrastructure optimization are examined. Cost-benefit analysis of capital expenditure and operational expenditure towards fuel, logistics, transportation, and maintenance are discussed. These are considered against known desalination costs to determine geographical and distance-based thresholds where maritime transport becomes competitive. By bridging gaps between decommissioned maritime assets and acute freshwater deficits, the study provides a comprehensive framework for policy makers, marine engineers, and economists to enhance freshwater resilience using the existing global shipping capacity.

Keywords: Water scarcity; Repurposed oil-carriers; Freshwater Backhauling

Introduction

Freshwater, a vital resource to sustain life and various industrial processes, is under stress globally. Today, over one billion people lack access to freshwater. An additional 2.7 billion living in developing countries face water scarcity that lasts for at least one month a year [1]. Water usage is unsustainable because there is a gap between demand and recharge rates. Driven by climate volatility, rapid urbanization, and industrial growth, the available freshwater in aquifers and surface ecosystems has reduced drastically [2]. If current mismanagement of freshwater persists, the world will see a 40% gap between freshwater supply and demand by 2030 [3]. This would put more than 4.5 billion people under stress with about 700 million becoming migrants by 2030 [4]. Probably, freshwater scarcity will increase exponentially because of climate change, extreme weather events, increasing population, industrial manufacturing [5] and water-intensive agriculture [6,7], and an increasing use of Artificial Intelligence (AI) that demands substantial water for cooling [8]. This has resulted in a greater push by the United Nations to improve management of existing aquatic ecosystems and encourage sustainable development [9]. Since no two nations are equally endowed with this natural resource, the situation is already grim in some countries. Bangalore (India), Beijing (China), Cairo (Egypt), Jakarta (Indonesia), and Tokyo (Japan) are steadily running out of freshwater [10]. Only if economy-wide conservation actions are initiated will it be possible to delay water scarcity.

Converting saline seawater into quality potable water using desalination technology has increased. This technology faces strict physical, environmental, and financial constraints [11]. It is energy inefficient [12], causes noise pollution, emits gaseous emissions and chemical spills, causes harm to the aquatic life owing to increased concentration of salts, temperature, and specific weight of waste brine [13], and disturbs the salinity of the region through discharge of tailings with high concentration of salt [14]. In addition, these plants require high investment for construction and operations. Nevertheless, nearly half of Israel's water requirement is met by desalination. Similarly, most countries of Northern Africa, the Middle East, and most Small Island Developing States (SIDS) in the Indo-Pacific, find desalination a relatively cheaper option than importing potable water. Such is the demand that studies have reported a 40% increase in the installed capacity of these desalination plants between 2020 and end of 2025 [15]. Currently, desalination of seawater seems to be the only available option for obtaining freshwater.

There is now need for a mix of new technologies, sustainable practices, and collective efforts mainly through conservation and public involvement. Some solutions that are currently used to address local water stresses include water trucking, water purification tablets, conservation

techniques such as rainwater harvesting, water recycling, addressing leaks in water distribution systems, precision farming, and the use of smart technologies at home, and creating improved aquifers and water distribution systems both at the national and international level. Since supplementing water for water-scarce areas is a major concern, towing icebergs to arid regions has also been proposed [16]. In fact, the 2021 World Economic Forum (WEF) listed the harvesting of icebergs as one of the top five alternatives for addressing water stress. Though theoretically feasible, it requires significant energy and technology coupled with robust conservation and supply mechanisms. Other notable alternatives include use of solar-powered devices on the sea surface to evaporate and capture freshwater, use of advanced materials to absorb moisture from the air to provide localized drinking water, treating and reusing domestic wastewater, and deploying smart Internet of Things (IoT) networks and AI to detect leaks, optimize irrigation, and monitor municipal water networks in real time [17].

Akin to land-based water trucking, the use of repurposed oil-carriers to move water from freshwater-rich to freshwater-deficit areas has also been proposed. But their use has not been implemented because of economic and technological considerations [18]. It is important to understand that whereas global oil-shipping operates in a mature, standardized, and consolidated international commodity market, freshwater logistics are fragmented and restricted. Water is considered a low-value resource whose logistics are dictated by local geography, municipal infrastructure, and immediate regional scarcity [19]. It is thus essential to look at technological and economic challenges in the use of repurposed oil-carriers to address freshwater scarcity, especially for dry and arid regions of the world [20].

Using a desk-based qualitative research approach, the paper reviews and analyses the feasibility of using repurposed oil-carriers for meeting the requirements of water deficit countries by using freshwater backhauling. The work synthesizes open-source literature such as books, peer-reviewed papers, newspaper articles, study reports, policy documents, and websites. There is very little published on this topic. Hence, an ‘out-of-box thinking’ approach has been used to make educated estimations and conclusions with appropriate justification provided for every inference drawn. As a result, the paper provides a feasibility study and conceptual review that uses an exploratory case study approach for use of repurposed oil-carriers for the water trade. The study aims to provide some food for thought for policy-makers and industry alike for using such repurposed oil-carriers to address the growing water requirements. Future research should aim to integrate semi-structured interviews with marine engineers, port authorities, and environmental policy makers to gain

empirical insights into technical issues, regulatory bottlenecks, and transboundary water agreements that rudimentary literature analysis cannot fully capture.

The paper begins by providing the efforts made globally over the years to transport freshwater to regions with freshwater scarcity while examining the roles in which repurposed oil-carriers can be used in general and to address freshwater scarcity in particular. This will be followed by comparing existing oil and water logistics and understanding why oil logistics is successful but water logistics is not. Next, the paper examines the technical, engineering, and economic requirements to use repurposed oil-carriers in a freshwater backhauling role; and then a case study to strengthen the understanding and use of this method. A discussion and suggestions for ways ahead towards the possible use of repurposed oil-carriers will follow, before concluding the paper.

Transporting Freshwater by Sea

Oil-carriers or oil tankers, as they are usually referred to, are specialized merchant ships that are designed to transport oil products in bulk. They are broadly categorized into crude tankers (for moving unrefined oil) and product tankers (for moving refined petroleum products) to consumption markets. The tanker design is strictly governed by international maritime safety and environmental regulations. To minimize risk of oil spill caused by grounding, collision, or rupture of shell plating, double hull designs have become mandatory. The size of these ships varies according to the trade route and the canal dimensions they need to cross. Accordingly, they range from small coastal vessels to Ultra Large Crude Carriers (ULCCs) capable of carrying over 320,000 deadweight tons (DWT) of cargo. For efficient operations, these vessels require sophisticated cargo handling systems, including complex networks of pumps and piping for loading and unloading of their cargo; maintaining their stability by taking in seawater as ballast in specially designed tanks. As a safety measure, these ships use inert gas systems to replace atmospheric air in the cargo tanks with non-flammable gases to mitigate the risk of explosion of volatile hydrocarbon vapours.

Like all merchant vessels at sea, the operational lifespan of an oil tanker is strictly governed by regulations enforced by the International Maritime Organization (IMO), through the MARPOL Convention (Annex I), and typically spans 20 to 25 years unless explicit extensions are verified by flag state administrations. Once the design life of these vessels is completed, they need to be scrapped and broken down to be recycled.

After their design life of 20 to 25 years is completed, these ships are considered a hazard at sea that can cause oil-slicks and hence pollution if damaged. Their use in secondary roles is, however,

possible. Accordingly, these oil-carriers are used in secondary roles such as floating wastewater plants, living space for seaside population, providing potable water and different kinds of water for targeted application by using their desalination plants, and as a cost-effective solution for land-based structures for solar plants, wind-farms, and runways [21]. The tankers could even be converted into multi-storeyed car parks to address the growing problem of space for vehicles, or be converted into movable power stations by converting them into floating wave energy converters (WEC) [22]. Most of these innovation projects have been technically proven by EnvioNor [23] in partnership with the international aid organization Star of Hope International that educates children to create an impact on the world [24,25].

To supplement freshwater availability in remote regions, such as for small island states, water needs to be physically moved. This business of moving water in large quantities or bulk is broadly divided by source, transportation, and destination. The source is where water is available in plenty and is replenished naturally. The bulk transportation of this water is undertaken using ships and barges, but may be limited, owing to lack of loading and unloading facilities. Over the years this movement has shifted to barges as they are cheaper to operate and maintain. The destination of this bulk freshwater is the countries that lie in the hot arid regions or have been ravaged by climate-driven events that have resulted in water scarcity. Globally, many regions receive transported water nearly round the year. Nauru and islands in the Caribbean receive up to 30% of their water supply using tankers with that of the Caribbean coming from Andros Islands which are 60 km away [26]. Other noteworthy global water trade is by Turkey to North Cyprus [27], and the port of Marseille that supplied water to Spain and Italy in vegetable oil tankers suitably modified to carry water [28]. Several companies have used giant floating bags/ collapsible water bladders especially manufactured for water transportation to Greece since 1997. These bags/ bladders were towed by tugs but were prone to bursting [29].

Yet another way of transporting freshwater by ships is the use of oil-carriers which was first proposed in 1985 by the Japanese Classification Society, ClassNK, considering the movement of oil from Saudi Arabia to Japan and freshwater from Japan to Saudi Arabia [30]. These oil-carriers can be put to use to transport freshwater using the free cargo space and/ or segregated ballast tanks when the ship is returning to the oil loading port. This process is called freshwater backhauling (FWBH). Technically, FWBH is feasible after modifications and developing new shore-based infrastructure for loading and unloading of freshwater at both the oil loading and unloading ports. The freshwater may be carried either in ballast tanks or in the cargo tank itself. For corrosion protection, the ballast tanks require a glass reinforced or polyurethane coating. The cargo tanks will

remain protected because of the existing oil film of cargo discharge prior to taking in freshwater. On reaching the destination port, the freshwater would be treated according to the regulations of the recipient country and the quality of freshwater transported [31]. Though the FWBH has not been brought into actual practice, a patent on the entire process was filed in 2011 by a French company after adding processes to treat and clean the freshwater on their return passage or prior to unloading of the freshwater. The patent has been registered under the World Intellectual Property Organisation (WIPO) [32].

The proposed use areas discussed here are all technically feasible but may not be economically viable as conservative estimates of transportation at US$ 1.50/m^3 (from Japan to Saudi Arabia) are much higher than the desalination cost of US$ 0.60/m^3. The bigger challenge is to find an agency willing to operate the vessel in its changed configuration and connect it to the shore utilities for the function proposed. Like all efforts of this magnitude, it requires the will and the policy push of the policy-makers to make the proposal a business model that is acceptable to the industry. Since the design was proposed by ClassNK in 1985, the safety of the vessel and the environment and its functionality is considered beyond doubt. With regard to the FWBH, it is not covered by any Classification Society to date and hence needs greater deliberation for greater understanding to emphasize the need for Classification Societies to support the use of oil-carriers in a FWBH role to meet the growing global water crisis. Accordingly, FWBH will be discussed in greater detail both from a technical and economic point of view to show that use of repurposed oil-carriers needs more detailed planning.

Beyond these, some maritime operators like Maersk have focused on micro-solutions. The shipping giant using innovative systems to optimize fresh-water generation onboard their vessels have begun producing and storing the produced clean drinking water during their regular transits. This stored clean water can be delivered in containers to remote coastal areas facing scarcity [33]. Table 1 shows a cost-benefit analysis of desalination that needs to be challenged by the FWBH. It is important to mention that these costs will change upwards in the event of conflicts as seen in US-Israel-Iran wherein desalination plants in Iran have been targeted and destroyed by the US forces [34].

Table 1: Desalination Cost-Benefit Analysis (Source: Author, from various resources)

Category	Specific Element	Details and Values (per m^3)
Financial Costs	Capital Expenditure (CAPEX)	**$0.25 – $0.45**: High plant construction costs.
	Operational Expenditure (OPEX)	**$0.15 – $0.25**: Membrane replacement and chemical treatment.
	Energy Consumption	**$0.20 – $0.35**: High-pressure pumping (requires 3–4 kWh/m^3).
Environmental Costs	Marine Ecosystem Impact	**High**: Discharges toxic, concentrated brine that depletes oxygen levels.
Logistical Benefits	Transportation & Logistics	**$0.00**: Produced locally directly at the coastline, eliminating freight fees.
Strategic Benefits	Fresh Water Security	**Vital**: Provides a reliable, continuous alternative for water-parched regions.
Overall Economic Baseline	Total Financial Cost	**$0.60 – $1.05**: Currently cheaper and more viable than maritime backhaul shipping.

Comparing Oil and Freshwater Logistics

The first question is why oil trade is successful but freshwater trade never gained traction even though the Middle East countries are the most impacted by a freshwater crisis. The simple answer is that the entire supply chain of the oil industry is managed by a small network of national oil companies and specialized global shipping fleets. As a result, the pipeline, storage hubs, and other support systems are universal. This allows a tanker to deliver cargo to any port in any part of the world. All this is feasible because oil is traded via high global future contracts that allow logisticians to hedge transportation risks [19]. On the other hand, freshwater logistics are fragmented and not economically lucrative as water is a low-value commodity which has localized management with a subsidised pricing structure as access to freshwater is considered a fundamental right of all human beings. Being heavier than oil (1 litre of freshwater weighs 1kg but it is 0.85~0.95 kg for oil), it requires more energy to move, whether through pipelines, bags, or by barges [35]. Governments supply freshwater at highly subsidized rates because it is a basic necessity. This makes third-party investment in water transport unviable [36]. An unpredictable freshwater requirement makes usage of assets such as tankers and barges unpredictable, destroying any guaranteed return on investment. These factors have prevented development of intermodal

infrastructure and use of modern digital infrastructure for tracking suppliers and distribution hubs for water transportation, leading to line losses and operational inefficiencies and hence reduced profits [37]. This furthermore makes a global spot price for freshwater impossible, with the rate being driven by the freshwater crisis prevailing in a region or country.

Although using repurposed oil-carriers may be a practical option for addressing water scarcity, this option is considered a stopgap arrangement to address local emergencies rather than provide a permanent solution. Even though oil-carrier ships have a high potential to carry freshwater because of their capacity, the amount of water carried in a Very Large Crude Carrier (VLCC) is only about 320,000 m^3 (2 million barrels or 320,000,000 litres) which is consumed by a major city (i.e., a large, heavily populated urban centre, serves as a primary hub for business, culture, and government, usually with a population of over 100,000) in a matter of days (at a global average of 100 litres per person per day). To add to this, ocean freight is expensive, cost increasing with distance travelled. Hence such movement of bulk water in ships becomes uneconomical over distances greater than 884 km [38]. Potable freshwater, when transported in active oil-carriers, is likely to be contaminated because of residual oil in the tanks. If these residues have to be removed, the cost associated with cleaning and making the tanks ready for carrying potable water will be very high and time consuming [39]. These added activities make logistics of freshwater movement by ships highly inefficient.

Technical and Engineering Requirements

Major oil exporting countries in the Middle East (i.e., those that extract more crude oil than they consume) experience arid conditions and have not been endowed with the natural resource of freshwater. Since the natural climate is ‘dry’ in the Middle East, these countries remain water deficient for most of the year. Saudi Arabia, UAE, Oman, Qatar, Kuwait, and Bahrain have no rivers or freshwater lakes. They do, however, have large reservoirs that geologically trap groundwater, which is the main source of freshwater for these countries. Small dams are also constructed to increase the groundwater recharge. With these countries experiencing economic growth from sale of oil, both their population and social development has seen an increased growth. This has resulted in increased demand for freshwater which is currently met by desalination. There have been plans to replace the existing desalted water with natural groundwater [40]. This has required looking at alternatives which include using shuttle tankers to get freshwater from Pakistan and Turkey [40].

Since oil tankers delivering crude oil to various parts of the world have to come back to the originating country without any return cargo, there is a possibility of filling freshwater in place of oil and ballast in the return voyage from the country where crude has been delivered. Such a mechanism is called freshwater backhauling (FWBH). It can effectively address the water shortage in oil-producing, water-deficient countries. While this procedure is possible for every type of cargo vessel, such as bulk carriers and container vessels, we will limit our discussion to oil-carriers. As mentioned earlier, the concept was researched extensively in the 1970 and 1980s during the turbulence in the oil markets, but ceased to get attention abruptly when the global economy recovered. FWBH reduces emissions in the return passage and solves the problem of movement of invasive species across maritime boundaries as the ballast water is now replaced by freshwater from the oil-importing nation [41]. Still, it has received little attention. With increasing focus on decarbonization of the shipping industry and control of invasive species, the subject needs to be revisited as it also addresses the issue of the global water crisis.

As discussed above, the use of dedicated tankers for freshwater transport is cost-prohibitive when compared to other options such as desalination. If turnaround time in port because of loading of freshwater is not high, freshwater transported as ballast would add minimally to the cost – making it cheaper than when dedicated vessels are used. In the case of segregated ballast tanks being used for carrying freshwater, the need for costly ballast water cleaning systems can be eliminated, an economic advantage. Since the existing design and construction of oil carriers do not make them automatically compatible for being used as freshwater carriers, these ships need to undergo technical modifications. Similarly, since the port-side infrastructure currently does not cater for handling loading and unloading of freshwater, this infrastructure too would require modifications. Accordingly, the minimum essential modifications required to make FWBH successful are now discussed.

Modifications on the Vessels

The existing oil-carriers are not aligned to carry potable freshwater as the coating used by oil carriers does not prevent water toxicity and contamination. Since the unloading and transfer of crude oil onboard is done by an independent system onboard, these too need to be examined and modified where required. The following modifications are considered critical to ensure that freshwater as a backhaul can be handled by the oil-carrier.

(a) *Pumping Head Enhancement*: Ballast pumps require an increased discharge head of 100–150 metres to transfer water to shore-based storage to cater for shore-side static heads, frictional loss in shore-based pipelines, overcoming back pressure from shore-based tanks, and high resistance of shore-based filtration systems. This requires augmenting capacity of existing pumps, installing intermediate deck pumps, or using independent submersible pumps of approximately 1,000 m^3/hr capacity.

(b) *Deck Manifolds and Piping*: A separate set of hoses and manifolds are required to be installed for freshwater handling. These manifolds must be installed on the deck near oil manifolds to avoid the need for installing new hose-handling davits for freshwater. Such dedicated hoses prevent water contamination and ensure purity of the freshwater.

(c) *Tank Vent Redesign*: With freshwater being used for ballast in place of sea-water, the tank venting systems needs to be structurally re-engineered to handle the new pressure dynamics and prevent failure of ship structure due to over pressurisation.

(d) *Anti-Corrosion Tank Coatings*: Ballast tanks are coated with copper and lead leaching paints to protect them against marine organisms present in the seawater used for ballast. If copper and lead are allowed to leach into the freshwater, it can make the water unfit for use. Hence, there is a need to recoat the ballast tanks with polyurethane or glass-reinforced plastic paints.

(e) *Strength of ships*. Freshwater has higher density than oil and so is heavier than oil. Since the oil-carriers are structurally designed for a lower density fluid, structural strength analysis for an increased density fluid would need to be undertaken prior to use for transport of water. Although the problem can be addressed by loading a lesser quantity of freshwater, this would result in sloshing and free-surface effect that would result in loss of stability of the ship at sea. Only detailed calculations would define the limitations over which these oil-carriers can operate with freshwater as cargo in place of crude oil.

(f) *Considering suggestions of patent*. The onboard water treatment and clean freshwater storage system proposed in the patent on FWBH taken in 2011 [32] and discussed earlier can be

experimented with. Use of this proposed methodology will ensure that minimum treatment of the transported water is required after it has reached its destination port.

Improvement of Marine Infrastructure at Ports

To load and unload freshwater in an oil-carrier there is a requirement of providing specialized equipment that can handle freshwater without contaminating it. Currently, most large oil-carriers cannot come alongside conventional piers and hence operate from specialized mooring points which need to be augmented with specialized facilities to load and unload freshwater. Accordingly, some modifications would be required at these ports. Some of these modifications are discussed here.

(a) *Offshore Loading and Unloading*: To load and unload cargo from large oil-carriers that cannot come alongside conventional piers, specialized mooring points using Single Point Mooring (SPM) buoys or advanced offshore mooring technologies like HiLoad systems are used. Conventional SPMs are designed to handle only one single cargo. Advanced SPMs can handle multiple distinct products to avoid contamination. Hence, the existing SPMs would need to be modernized to handle multiple fluids.

(b) *Storage Reservoirs*: Crude oil is loaded in oil-carriers from onshore storage facilities that have a high-volume of buffering (typically 70,000 to 150,000 DWT per vessel). If freshwater has to be loaded/ unloaded from these ships, similar specialized facilities are considered a basic essential to ensure minimum time in port.

(c) *Water Treatment Facilities*: The freshwater unloaded from the ship would need to be purified prior to use and may require site-specific infrastructure. Infrastructure comprising removal of fine coalescence and polishing filtration activities for purification [42] is considered necessary to ensure effective use of the transported freshwater for drinking, agriculture, or any other purpose.

Using Segregated Ballast Tanks (SBT) and converted cargo spaces for FWBH.

By using both techniques, viz. SBTs and cargo spaces, the volumetric efficiency of Freshwater Backhauling (FWBH) can be enhanced. Each method requires completely different infrastructure modifications, pumping systems, and water treatment strategies.

Segregated Ballast Tanks (SBT)

SBTs are provided as isolated spaces exclusively for stability. They prevent direct contact of the cargo with the environment in the event of grounding, collision, or rupture of the shell plating. By using SBTs for freshwater, the likely contamination from oil residues can be avoided requiring lesser efforts for purification. Care needs to be taken to change the coating of these tanks from the currently used leaching paint to a glass reinforced plastic or polyurethane to avoid contamination of the freshwater. In addition, high volumetric pumps would need to be provided to maintain the desired discharge head.

Converted Cargo Spaces

By using the cargo space as additional space for transporting freshwater, an increased quantity of water can be transported. But use of this space introduces hydrocarbons as contaminants in the freshwater. Cleaning of these cargo tanks is cost prohibitive and would increase time in harbour This increases the overall cost of freshwater transportation, which is undesirable. The oil present acts as a barrier between freshwater and the tank structure avoiding any chances of corrosion. Since the main cargo pumps are of high capacity, they need no modification and can be used to pump out freshwater. But port facilities to receive, handle oil contaminants, and filtration of the freshwater using synthetic resins or ceramic blocks would need to be created. Freshwater carried in cargo space is considered fit for industrial and agriculture use after minimum essential purification.

Towards an Economic Viability Framework

No proposal or project is considered viable unless its economic viability can be ascertained. This can convince the investors that the proposal is economically competitive. Since the FWBH operation has numerous variables that depend on an array of parameters, the most appropriate method for economic viability assessment is to create a mathematical economic model. One such model for FWBH has been discussed by Sharma and Lande in their Norwegian Master's thesis [31]. Using this model, if we consider an average cost of desalination at US$ 0.70, a dedicated tanker transportation system would be difficult to operate since moderate to high rates of operating a dedicated tanker make the transportation uneconomical. But, Freshwater Backhauling (FWBH)

is considered technically feasible and economically competitive as it will be able to deliver freshwater to arid regions at approximately US$ 0.83 to 1.16 per ton for trips between Japan and Saudi Arabia. This is calculated considering the movement of nearly 50-200 million tons of freshwater annually using double-hull Suezmax, VLCC, and ULCC tankers.

It is seen that this cost would reduce if freshwater would be carried in both segregated ballast space and in cargo tanks. The process is also much cheaper than building and operating dedicated freshwater tankers. This said, the cost of infrastructure – which is a one-time investment – has not been catered for in this calculation but is considered essential to be undertaken for FWBH to be successful. It is important to note that use of these oil-carriers in an alternative role depends on the prevailing global oil market conditions as the movement of these oil-carriers is driven by oil prices and geopolitical situations. The supply of freshwater to countries through FWBH may not be a completely reliable method for arid and water parched countries. The economic advantage of moving freshwater using repurposed oil-carriers would only increase when the cost of production of purified natural water rises, thereby reducing the cost differential between the produced and transported water [43].

The argument of economic viability is considered valid as long as alternatives of obtaining freshwater, say through desalination are available. If aggressors exploit ecological and infrastructure fragility during conflicts by damaging desalination plants to make them non-operational [34], as seen in the US-Israel-Iran conflict, the need for water trade by Iran becomes a necessity rather than a desire. It is no wonder that countries are looking at various alternatives to ensure water security including creating strategic storage capacities [20], use of nature based solutions [44], and import of water using pipelines [40]. It is recommended that along with these methods, FWBH can be actively considered as a means of achieving water security. With use of Sovereign Wealth Funds in water-scarce Middle East countries, experimenting with FWBH should not be difficult.

Other than these direct economic advantages, there are other advantages of using FWBH. These include disallowing movement of invasive species across maritime boundaries and reduction of carbon emissions as the return passage is undertaken in a fully loaded condition. These tacit advantages align well with the present efforts of the GCC countries to shift away from a fossil fuel based economy [45] and hence must be explored and used by them. Additionally, FWBH helps overcome the challenges of environmental degradation by desalination plants. It also ensures that job opportunities are created for people within the country through related projects and actual import of freshwater. A case in point is the US$ 700 million worth of infrastructure projects that

Israeli companies gained after the deal of freshwater trade was signed between Israel and Turkey [46]. Such exports can improve relations between two countries, and may also be used as a geopolitical tool if relations deteriorate.

Case Study

To strengthen the argument that use of repurposed oil-carriers should be encouraged for transportation of bulk freshwater from water-rich countries to water-deficit countries. Accordingly, we now discuss a case study of water supply from Turkey to Middle East countries from the Manavgat River using backhaul logistics. Turkey proposed the project. As part of the project, Israel agreed to purchase 50 MCM (Million Cubic Metres) of water annually for 20 years from Turkey in 2004.The agreement was subsequently shelved in November 2006 because the parties had neither settled the price nor selected the company to implement the water transfer. Rather than relying on water backhaul, Turkey chose a more reliable subsea infrastructure creation in the form of subsea pipelines to supply water to Northern Cyprus that allows movement of 75 MCM of water annually via a fixed anchor line [47]. Understanding the project helps understand the actual possibility and feasibility of repurposing oil-carriers to address water scarcity.

The Manavgat River Project

Manavgat River of Turkey discharges into the Mediterranean Sea. Approximately 6 MCM is considered ‘lost’ to the sea on a daily basis. Realizing that the entire Middle East consumes approximately 10 MCM of fresh water daily using desalination plants, Turkey has built maritime loading infrastructure at the mouth of the river to filter, store, and pump water directly into deep-sea vessels. The project commenced in 1992. Turkey’s General Directorate of State Hydraulic Works (DSI) was permitted to develop water supply for domestic use. Accordingly, water from the river is pumped up to the purification plant using a pumping system. The purification plants undertake chemical and physical water treatment to meet WHO standards [48]. These plants are situated at a height of 67 metres above the mean sea level where a water tank of 500,000 m^3 stores half of the supplied water as treated water and the other half as raw water. The water from these tanks is supplied to two separate Single Point Mooring (SPM) points – one for raw water and the other for purified water – both by gravity. See Figure 1.

The Manavgat river freshwater supply project is designed to export 180 MCM of freshwater annually. The purification plant is capable of filtering 250,000 m^3 of purified water daily – alongside an equal volume of raw water [49]. To support the movement of freshwater to the ships, dual undersea pipelines extend 12 km out into the Mediterranean Sea, terminating at two Single Point Mooring (SPM) buoys. These buoys permit large vessels (60,000 to 250,000 DWT) to fill their holds directly from the sea terminal [49].

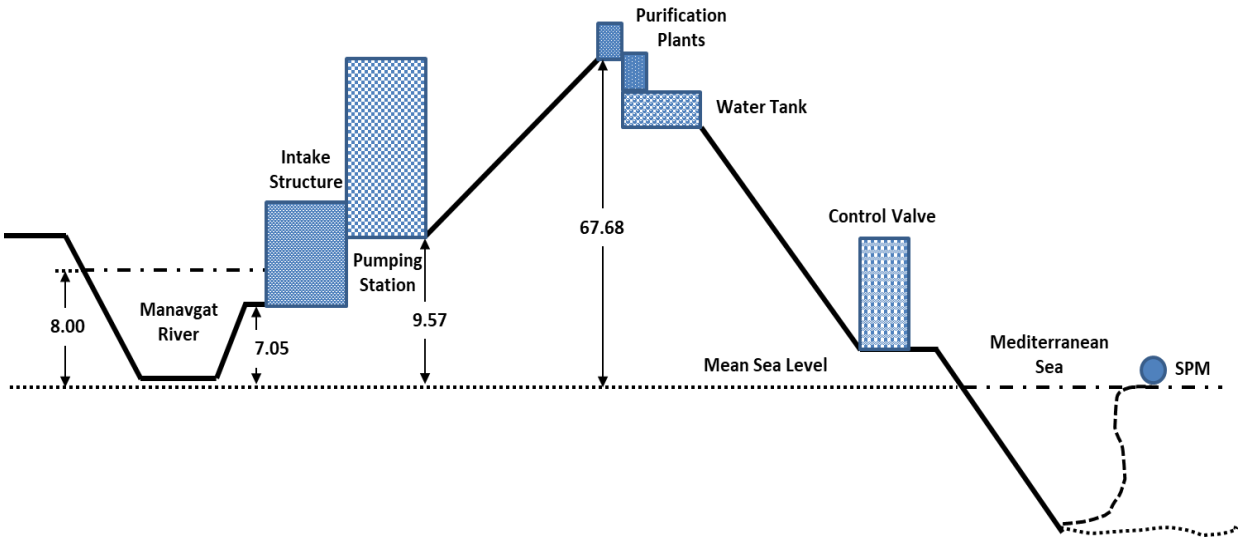

Figure 1. Schematic of Manavgat River Project [50]

The Manavgat River Backhaul Water Logistics

The deep-sea vessels used for transportation of water include converted oil supertankers, specialized towing bags (made of Medusa fabric), and crude oil, liquefied natural gas (LNG), and liquefied petroleum gas (LPG) tankers, that otherwise would sail from Turkey to Saudi Arabia completely empty after unloading their cargo in Turkey [46]. As part of the Backhaul Water Logistics strategy, these ships replace the seawater carried in ballast tanks for structural stability with freshwater from the Manavgat River [47]. As a result, the fleet usage is optimized by 30%, the water cost in Middle East countries can drop by 30%, and the cost of infrastructure creation towards new desalination plants can be saved. On the environment side, backhaul logistics have allowed reduced carbon emission from ships on their return passage. They have ensured that invasive species from the Mediterranean do not move to the Arabian Sea. Additionally, the ecological burden created by desalination plants of the Middle East has been reduced.

Limitations

Although the project is considered as an initiative towards increasing regional security and stability, dependence on an external sovereign country for a critical resource, freshwater, is something most countries would like to avoid. Such dependence gives the supplying country the option to use water as a geopolitical tool. The same cannot be said for oil wherein the possible suppliers are diverse. The limitation of this freshwater trade to remain economical is its distance, which is recommended to be less than 884 km [38].

This distance is maintained and the necessary ships are available, but care is required to ensure that the withdrawal rate of freshwater is lower than the charging rate for sustainable use. Furthermore, the impact of water withdrawal on sediment deposition and the health of the local ecology requires greater scrutiny. The environmental and social impacts from building and operating the freshwater transfer infrastructure need to be considered [51].

Economic Viability

The economic viability of backhauling freshwater from the Manavgat River is examined by comparing the total costs per cubic metre (m^3) transported via backhauling against Seawater Reverse Osmosis (SWRO) desalination, which currently provides a baseline price of water in the Middle East. With improvement in desalination technologies, this economic viability has become challenging [52]. Considering the CAPEX, OPEX, energy consumption, logistics, and transportation the comparative values as obtained for a backhaul and desalination methods is seen in Table 2 below. One notices that with the desalination baseline (US$ 0.60 to 1.05) being less than Manavgat Backhaul Shipping (US$ 0.70 to 1.40), the backhaul method is not viable economically – but still remains competitive in certain circumstances. It would become acceptable only if either the cost of local electricity in the Middle East rises above US$ 0.20/kWh or where there is an urgent need to meet freshwater requirements until a new desalination plant can be constructed.

Table 2: Comprehensive cost structure of water supply and production in the Middle East countries (Source: Author from various resources)

Cost Component	Backhaul of water from Manavgat River	Modern SWRO Desalination
Capital Expenditure (CAPEX)	**$0.15 – $0.30** (Low onboarding infrastructure)	**$0.25 – $0.45** (High plant construction costs)
Operational Expenditure (OPEX)	**$0.10 – $0.15** (Source water extraction & treatment)	**$0.15 – $0.25** (Membrane replacement, chemicals)
Energy Consumption	**$0.05 – $0.10** (Low-pressure pumping)	**$0.20 – $0.35** (High-pressure pumping: 3–4 kWh/m^3)
Logistics and Transportation	**$0.40 – $0.85** (Vessel charter, port fees, cleaning)	**$0.00** (Produced locally at the coastline)
Total Cost	**$0.70 – $1.40 / m^3**	**$0.60 – $1.05 / m^3**

Discussion and a Way Ahead

Freshwater scarcity has been a challenge for many countries because of climate-driven events and an increasing population. This has forced countries to consider steps toward sustainable water resource management approaches. It is essential to educate people to conserve and judiciously use available water resources, and managing these resources equitably is also essential. This means transboundary cooperation and agreements. These complications and the fact that freshwater is an essential resource have tended to strengthen the argument for desalination. This has allowed the technology to reduce the costs in a high-capacity SWRO plant to be as low as US$ 0.28 /m^3. With desalination having its own environmental concerns, freshwater trade should be investigated.

Even though export of water from water rich sources has been happening for many centuries, it has not been a formal trade because of the low cost of water and the costs and efforts in transporting water using dedicated vessels. To minimize the cost associated with specialized vessels, and to make optimal use of the return passage of an oil-carrier involved in export of oil, ClassNK undertook a feasibility study of using repurposed oil-carriers to transport water in segregated ballast tanks and oil cargo tanks in 1985. Such repurposing of oil-carriers was found to be technically feasible and economically competitive – but did not develop for lack of investors. The closest it reached reality was with the Manavgat Backhaul Water project of Turkey, where it aimed to supply water from the Manavgat River to the Middle East countries and Eastern Mediterranean countries including Israel. Turkey, under an agreement with Israel, modernized the infrastructure of its ports and supply systems but the agreement was shelved within two years of its signing. The main reason for this cancellation was Turkey's increase in the price of transported water. This increase was a

result of the high global cost of fuel and increased cost of purification caused by the privatization of water treatment facilities by Turkey [53]. As a result, Israel shifted their focus towards developing desalination technology.

The threat to freshwater security is real, and demands action. With advances in technology, it is now possible to conserve existing natural water resources while transforming alternative ones into a source of high-quality freshwater. This effort requires political cooperation in conserving freshwater sources that may be in rivers, lakes, on surface, or in groundwater resources. But geopolitical considerations and fear that one country may use lack or abundance of freshwater as a geopolitical weapon to gain leverage against another impedes such cooperation. If the freshwater resources used for export are over-exploited, they may lead to freshwater scarcity in the exporting nation – thereby creating freshwater scarcity and even ecological damage for them. Turkey began by exporting freshwater from the Manavgat River but today finds that the water table of the country has reduced drastically. With a growing internal freshwater demand, if adequate corrective actions are not taken, Turkey too may end up facing freshwater scarcity [47].

The present study addressed the use of repurposed oil-carriers for transporting freshwater in order to meet global water scarcity. The study has shown that the entire process of using repurposed ships is technically feasible and economically competitive under certain conditions. But first there is a need for interested stakeholders and investors. As demand for freshwater increases with increasing populations and a greater demand for industrialization, agriculture, and rise of Artificial Intelligence, the time is fast approaching when water trade would become economically lucrative as oil is today.

It will probably not be long before water diplomacy and water trade becomes an independent branch of International Relations. Currently, freshwater is not a traditional commodity but it is traded for money globally within countries in the form of packaged drinking water [54]. Movement from intra-country trading to inter-country trading is a matter of time. It will entirely depend on how seriously sustainable means are used to preserve existing freshwater resources and the reclamation of wastewater.

It may seem unlikely that ship owners will accept enormous costs for fitting manifolds, pumping arrangements, and recoating segregated ballast tanks. The shore-based infrastructure to load and receive water from tankers may be non-existent and a costly arrangement. The odds for scrapping a 20 to 25 year old tanker may be high. As global temperatures increase through climate change, the demand for freshwater is only going to increase. This and the growth in world population will increase the stress on terrestrial freshwater resources making freshwater availability scarce.

Freshwater will then become an essential commodity within the world trading system. But if this trade in freshwater is not handled sustainably, it would only lead to environmental deterioration. It is thus imperative that adequate studies are undertaken to take the concept of FWBH to a logical usable conclusion. We may not use it immediately, but we will be ready when the time is ripe.

The present study shows that the FWBH concept needs to move from theory to practice. It is essential that a localized pilot project be launched as a scenario-specific project on a single route. This project needs to be between a freshwater-surplus oil-importer and a freshwater-deficit oil-exporter to monitor coating durability, cross-contamination, and pump efficiencies in real-time. The Manavgat River project can be considered as a model project for such studies. To take the concept forward as a formal standardized framework, public authorities and global trade bodies such as the International Maritime Organization (IMO) and the World Trade Organization (WTO) must become engaged with the reality of the problem, and its possible solution. Such involvement will help resolve the economic status of bulk freshwater and institute long-term, stable public contracts instead of volatile spot market agreements. Additionally, newly constructed ships and those undergoing major refits must align to FWBH design to let ship owners leverage freshwater transport as a compliance exemption, lowering operational treatment costs, and avoid cost of retrofitting at the end of service life.

As part of repurposing oil-carriers, ships that have lived their service life can be additionally used as floating wastewater plants, or to provide different kinds of water through desalination, for movable power stations using wave energy convertors, or living space to overcome non-availability of land, for creating land structures including runways in the sea, or as multi-storeyed car parks. Since most of these proposals have been proven as feasible, the need of the hour is public-private partnership to expedite change.

Conclusion

The study has examined the use of repurposed oil-carriers for addressing global water scarcity. Although a number of proposals have been found to be technically feasible, none of them has moved up the Technology Readiness Level (TRL) ladder so as to be proven as economically viable. Therefore, it is difficult to say whether FWBH is a feasible option in the global freshwater crisis or not. One realizes that this feasibility depends on the mode of operation, the market condition of global oil, the price of electricity in countries using desalination plants, the location of ports and terminals, as well as the influence of environmentalists to challenge the extensive use of

desalination plants. When compared at the environmental scale, FWBH is an option superior to desalination. Still, no full-scale FWBH project has seen the light of day so far. The international trading of freshwater must become a reality. The present study thus makes an effort to accelerate thought towards implementing a localized pilot project to study the FWBH proposal closely and in real-time so as to be future-ready.

Disclaimer

The views expressed in the paper are that of the author. They do not reflect the views or policies of the Government of India or the Indian Navy.

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Development of Hydrophobic Coating and Spraying System for Corrosion Resistant Coatings

Andrius Patapas [1,a], Aziz Fihri [2,b*], Yassine Malajati [2,c], Remi Mahfouz [2,d], Waleed Al-Nasser [2,e], Paul Luckham [1,f*]

[1]*Department of Chemical Engineering, Imperial College London, London, United Kingdom*

[2]*Advanced Materials Division, Research & Innovation Complex, Saudi Aramco, Dhahran 31311, Saudi Arabia*

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[a] ***ORCID***: *0009-0008-3315-466X;* ***Email:*** *andrius.patapas15@imperial.ac.uk*

[b] ***ORCID***: *0009-0000-0625-3568;* ***Email:*** *aziz.fihri@aramco.com*

[c] ***ORCID***: *0000-0002-9053-7017;* ***Email:*** *Yassine.Malajati@aramco.com*

[d] ***ORCID***: *0000-0003-0981-0440;* ***Email:*** *remi.mahfouz@aramco.com*

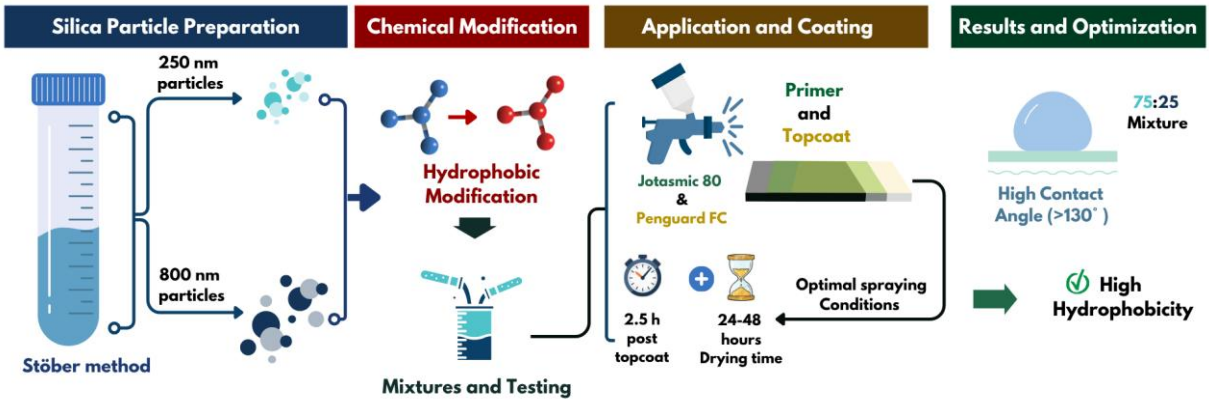
[e] ***ORCID***: *0000-0001-7372-9511;* ***Email:*** *Waleed.nasser@aramco.com*

[f] ***ORCID***: *0000-0002-8191-540X;* ***Email:*** *p.luckham01@imperial.ac.uk*

*** Corresponding authors:** Aziz Fihri, ***Email***: *aziz.fihri@aramco.com;* Paul Luckham, ***Email***: *p.luckham01@imperial.ac.uk*

Graphical Abstract

Hydrophilic silica particles of 250 nm and 800 nm were synthesized using the Stöber method and subsequently modified to obtain hydrophobic properties, confirmed by sessile drop measurements. Mild steel sheets were prepared, coated with Jotamastic 80 primer and Penguard FC topcoat, and then sprayed with different combinations of hydrophobic particles to form uniform coatings, which were evaluated qualitatively and through surface characterization techniques. The highest hydrophobicity (contact angle up to 140°) and optimal adhesion were achieved with a 75% (250 nm) and 25% (800 nm) mixture applied 2.5 hours after topcoat, with best structural formation observed after 24-48 hours of drying.



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Abstract: In this paper, hydrophilic silica particles (250 nm and 800 nm) were synthesized using the well-established Stöber method**.** The particles and their mixtures were chemically treated to achieve hydrophobic properties, confirmed using the sessile drop technique. Mild steel sheets were prepared, sand blasted and cleaned to the required surface roughness and cleanliness, verified by established quantitative methods. Two resins, Jotamastic 80 and Penguard FC, were applied as primer and topcoat to the required thickness. The resulting films were evaluated qualitatively and by optical interferometry and micrograph analysis. Samples were then coated with selected combinations of hydrophobic particles to form homogeneous coatings, and their hydrophobicity was assessed. The highest contact angle was obtained for a mixture of 75% 250 nm and 25% 800 nm particles, with other combinations showing contact angles between 130° and 140°. Optimal adhesion and hydrophobic performance were achieved when particle/ethanol suspensions were sprayed 2.5 h after topcoat application. The hydrophobic structure was best developed after 24–48 h of drying. Surface morphology was examined using Scanning Electron Microscopy, and the results are discussed.

Keywords: *Hydrophobicity, Steel structures, Spray coating, Contact angle.*

Introduction

Nature has long served as a source of inspiration for scientists, particularly in the study of natural surfaces that exhibit unique properties. One such example is the lotus leaf, which demonstrates superhydrophobic behaviour [1]. Inspired by such natural phenomena, researchers have focused on mimicking the micro/nanostructures of the lotus leaf to engineer synthetic superhydrophobic surfaces and develop innovative materials with enhanced properties [2]. These superhydrophobic surfaces have gained significant attention for their potential applications in various industries, including self-cleaning materials, anti-icing surfaces, drag reduction, oil-water separation and corrosion thanks to their excellent water repellency and antifouling properties [3,4]. But, their susceptibility to easy scraping and peeling remains a significant disadvantage that hinders their broader application in anti-corrosion fields. The fabrication of superhydrophobic surfaces requires combining suitable surface roughness with low surface energy materials and many processes have been explored to produce these surfaces, such as electrochemical deposition and plasma treatment, chemical etching and others [5-9].

Steel, a widely used material in industrial applications for its affordability and mechanical strength, is prone to corrosion in harsh environments [10]. The oil and gas company relied on cathodic protection, or coating to extend service life metallic structures and enhance safety and minimize economic losses [11,12].

Organic coatings, especially epoxy resins cured with amine agents, are frequently used to shield steel from corrosion. Despite these advantages, such coatings may degrade in marine environments under moisture exposure, leading to delamination and reduced durability. Nanoparticles such as silica, zinc oxide, titanium oxide, copper oxide, and fluorographene combined with polymers such as epoxy, polystyrene, polyurethane, and polydimethylsiloxane are being explored to develop superhydrophobic surfaces [13-18]. Silica is widely employed across industries because of its low cost, stability and versatile synthesis routes [19-22]. The Stöber method, the hydrolysis and condensation of alkoxysilanes in a basic medium, is commonly used to produce monodisperse silica particles with controlled properties [23]. To enhance their utility, the hydrophilic nature of silica can be transformed into hydrophobicity through processes like silanization [24,25]. In this study, hydrophilic silica particles of two sizes, 250 nm and 800 nm, were synthesized using the Stöber method. These particles were then modified to become hydrophobic and subsequently combined in different ratios. A combination of hydrophobic silica particles was dispersed in ethanol and applied via spraying onto an existing commercial epoxy coating system composed of both primer and topcoat layers. The highest contact angle was achieved using a mixture containing

75% 250 nm particles and 25% 800 nm particles. Other particle combinations also produced hydrophobic surfaces, with contact angles ranging between 130° and 140°. This study also outlines the optimized spraying conditions and parameters, such as dispersion concentration, flow rate, spray distance and topcoat drying time before application of the particle suspension.

Theory of Superhydrophobicity

The contact angle, θ is the angle formed when a liquid droplet in air meets a solid surface. It provides a measure of the relative strength of the interaction between the surface tensions at the three-phase contact line for two fluid phases and a solid surface (i.e., the border). It represents the ratio of the energy required to form a unit area of the solid-liquid interface to that required to form a liquid-air interface. This formalism was first proposed by Young in 1805 [26] and can be expressed mathematically as:

$$\cos\theta = \frac{\gamma_S - \gamma_{SL}}{\gamma_{LA}} \quad (1)$$

where γ_{SA}, γ_{SL} and γ_{LA} are the surface tensions at the solid-air, solid-liquid, and liquid-air interfaces, respectively. Although this is known as the Young equation, the original paper by Young contained no equations. The limitation of this approach is that the relation applies only to perfectly smooth, homogeneous surfaces. This was modified over a century later by Wenzel [27], who introduced a roughness parameter, *r*, defined as the ratio of the true area of contact of the droplet to the apparent contact area, such that the effective contact angle θ_E (the actual measured contact angle) is related to the true contact angle, θ, by the relation:

$$\cos\theta_E = r\cos\theta \quad (2)$$

The Wenzel model assumes that the liquid penetrates the grooves associated with surface roughness. This condition may not always occur, particularly if the surface repels the liquid. This case was examined by Cassie and Baxter [28], who considered the surface to consist of a series of pillars, such that the droplet rests on the top of the pillars and does not penetrate the gaps between them. Under these conditions, the effective contact angle, θE, can be given by:

$$\cos\theta_E = \sigma\cos\theta_1 - \sigma_2 \quad (3)$$

where σ_1 and σ_2 represent the fractional surface area in contact with the droplet and the fractional surface area corresponding to the space between the pillars, respectively, and θ_1 is the true contact angle of the surface. It is widely agreed that the water repellency of biological surfaces is explained by the Cassie-Baxter model. For example, duck feathers exhibit a topographical network of 'barbs and barbules', and a water droplet deposited on them remains in a solid-liquid-air non-wetting composite state, in which tiny air pockets are trapped, giving rise to a high contact angle. The most well-known biological example of a high contact angle is the lotus leaf, where the contact angle of a water droplet is about 160° [29].

The leaves of many plants are coated with a thin waxy layer which, if smooth, is likely to exhibit a contact angle similar to that of smooth polyethylene, of about 100° [30], yet the lotus leaf is not smooth. Lotus (*Nelumbo nucifera*) is a semi-aquatic plant with circular leaves reaching up to 30 cm in diameter and displaying remarkable water repellency. The upper surface of the leaf features a distinctive hierarchical structure consisting of small protuberances known as papillae, which are themselves covered with a dense coating of agglomerated wax tubules, giving the leaf its superhydrophobic character [31]. A hierarchical surface structure that induces strong water repellency and contact angles above 150° is not unique to lotus leaves. Neinhuis and Barthlott [32,33] surveyed more than 200 plant species with contact angles greater than 150°, many of which are less exotic, such as nasturtiums and cabbages. The advantage to the plant is that such strong water repellency ensures that water rolls off the surface of the leaf rapidly, removing dirt and pests in the process.

Experimental

Materials

Tetraethyl Orthosilicate (TEOS), ammonia in the form of an aqueous solution with a concentration of 32 %, ethanol and heptane purchased from Sigma-Aldrich, UK and used without further purification. Trichlorododecylsilane was purchased from the Tokyo Chemical Industry Co., Japan without further purification. The specimens used for this work were hot-rolled mild steel sheets (BS EN 10025 - S275JR), with dimensions of 150 mm x 100 mm × 5 mm, sourced from Orion Alloys Ltd., UK. Jotamastic 80 coating used as primer and Penguard FC, used as a topcoat, were purchased from Jotun, UK.

Preparation of hydrophilic silica particles

Silica particles of two sizes, namely 250 nm and 800 nm, were synthesized in 10- litre batches according to the well-established Stöber method [20]. Depending on the required particle size,

different amounts of tetraethyl orthosilicate, TEOS, ammonia and ethanol were used (see Table 1 for synthesis details). In all cases the mixture was stirred using a magnetic stirrer for 24 h at room temperature. Afterwards, the mixture was left for three days in a fume cupboard which served two purposes. Firstly, some ethanol and virtually all the ammonia evaporated, meaning the remaining volume was roughly halved and was safer to handle; secondly, the larger particles settled under gravity, allowing the remaining ethanol to be decanted off. Subsequently, these particles were redispersed in approximately 1 litre of ethanol and then centrifuged at 4000 g for 10 minutes to remove any impurities. The particles were then redispersed again in a similar volume of ethanol. Redispersion was simple with no aggregates observable to the eye. The smaller silica particles did not settle without centrifugation, so these particles were then centrifuged at 4000 g for 10 minutes and redispersed in ethanol twice producing a final volume of approximately 1 litre. The particle size distribution for each batch of in-house synthesized silica particles was measured using dynamic light scattering (Malvern μV instrument).

Table 1. Summary of synthesis conditions for the production of silica particles (~250 nm and ~800 nm) using the Stöber method.

TEOS (mL)	Ammonia (32 wt%) (mL)	Ethanol (mL)	Particle size (nm)
360	290	4500	~250
300	1500	3000	~800

Peak intensities for the batch of smaller particles were found to range between 220 nm and 290 nm (Figure 1), whereas those for the batch of larger particles ranged between 720 nm and 870 nm (Figure 2). Repeated measurements of independent samples allowed the mean particle size, polydispersity, and corresponding errors to be obtained (Table 2). Analysis using dynamic light scattering gave a polydispersity index of less than 0.05 for all samples, indicating that the samples were monodisperse, and that the errors were within reasonable limits

Table 2. Particle size measurements and corresponding statistics for silica particles with nominal sizes of ~250 nm and ~800 nm.

Particle size group	Mean particle size (nm)	Polydispersity index	Error (nm)
Small (~250 nm)	254.5 ± 4.6	0.020 ± 0.005	±26.6
Large (~800 nm)	803.6 ± 7.2	0.033 ± 0.008	±60.6

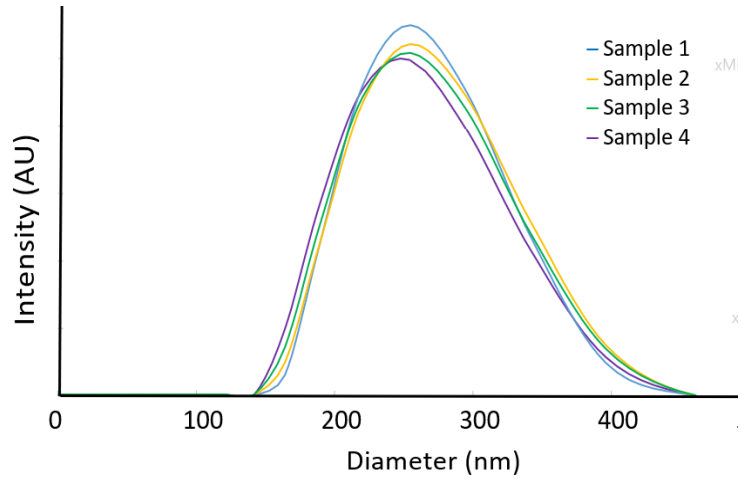

Figure 1. Particle size distribution of synthesized silica particles of smaller size

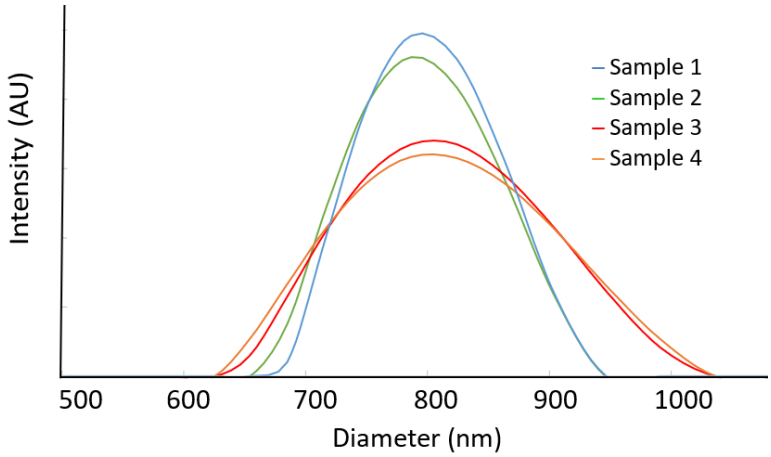

Figure 2. Particle size distribution of the silica particles of larger size

Preparation of Hydrophobic Silica Nanoparticles

Twenty grammes of silica particles, the small and large particles or mixtures thereof, were dispersed in 150 mL of dry heptane and stirred for 1 h at room temperature. The next step was to add 50 mL of trichlorododecylsilane; this mixture was stirred for 12 hours with a magnetic stirrer [29]. Particles were then centrifuged, washed in heptane, recentrifuged twice, and then dried in an oven set to 80 °C. The particles produced were noticeably hydrophobic. This procedure was conducted for the large silica particles, small silica particles and mixtures of the large and small silica particles. The mixtures investigated were by weight 25% large: 75% small, 50% large: 50% small. It was thought better to hydrophobe the mixtures of particles rather than mixing pre-hydrophobed particles owing to the difficulties of mixing powders, as opposed to suspensions.

Preparation of Hydrophobic Surface

The required by specification hot rolled mild steel sheets (BS EN 10025 - S275JR) cut to 150 mm by 100 mm (by 5 mm), were sourced from Orion Alloys Ltd., U.K. These coupons were abrasive blast using alumina powder followed by blowing with clean, dry, free of oil; compressed air was conducted in compliance with ISO 8501-1, which delivered cleanliness of near white metal (Sa $2\frac{1}{2}$). A residual dust level test was conducted in accordance with ISO 8502-3, and resulted in a rating of 1 [34]. Measurement of residual surface chloride was performed according to ISO 8502-6, and was found to be 35 mg/m² ± 15 mg/m²**.** The surface profile of the blasted metal sheets was analysed using an optical interferometer, which confirmed the roughness to range between 40 µm and 65 µm (Figure 3).

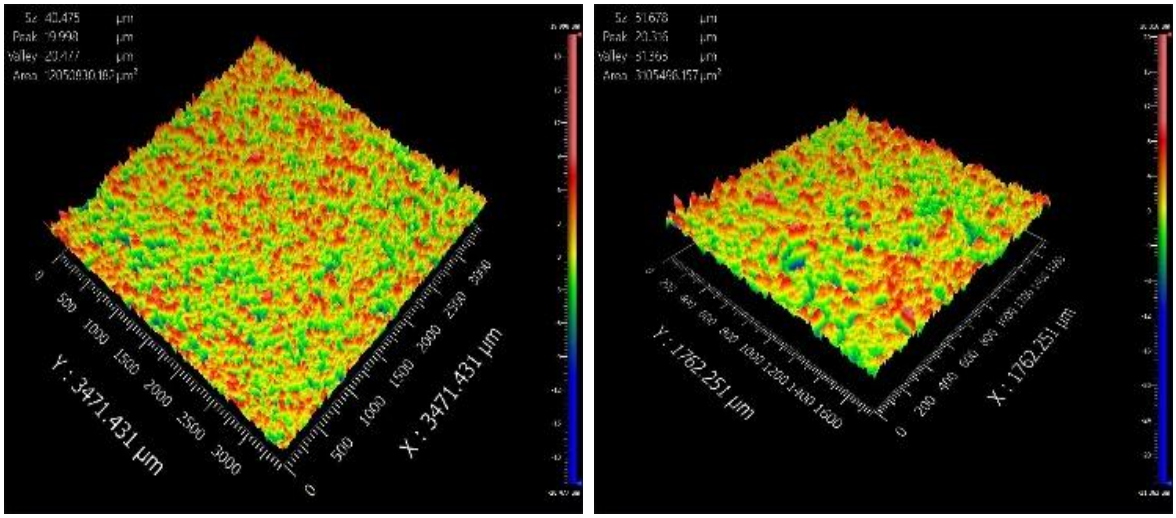

Figure 3. Typical surface roughness of the blasted metal sheet measured using optical interferometer (left: sample 1; right: sample 2)

After the aforementioned measurements and analyses of the blasted metal coupons, they were then firstly sprayed with the primer using a spray gun with compressed air at a pressure of 4 bar until the necessary film thickness was attained. The wet film thickness of the primer was measured using a hexagonal wet film comb and found to be about 210 μm ± 30 μm, which resulted in a dry film thickness of 150-200 μm (the latter measured using Neoteck VTMTL610 meter). A drying period of 24 hours was allowed at room temperature (25 °C ± 1.5 °C). Following this, the topcoat was then sprayed under the same conditions as the primer until the wet film thickness was measured to be between 250 μm and 300 μm, which resulted in 160-210 μm dry film thickness. Both coatings in the dry state need to be between 150 μm and 200 μm for optimal protection. Several metal

coupons were sacrificed to validate the spraying application method in terms of primer and topcoat film thickness. Three metal coupons were partially spray treated and the individual films allowed to dry. The film thicknesses of both the primer and the topcoat were confirmed to be within the required range using optical interferometer (Figure 4).

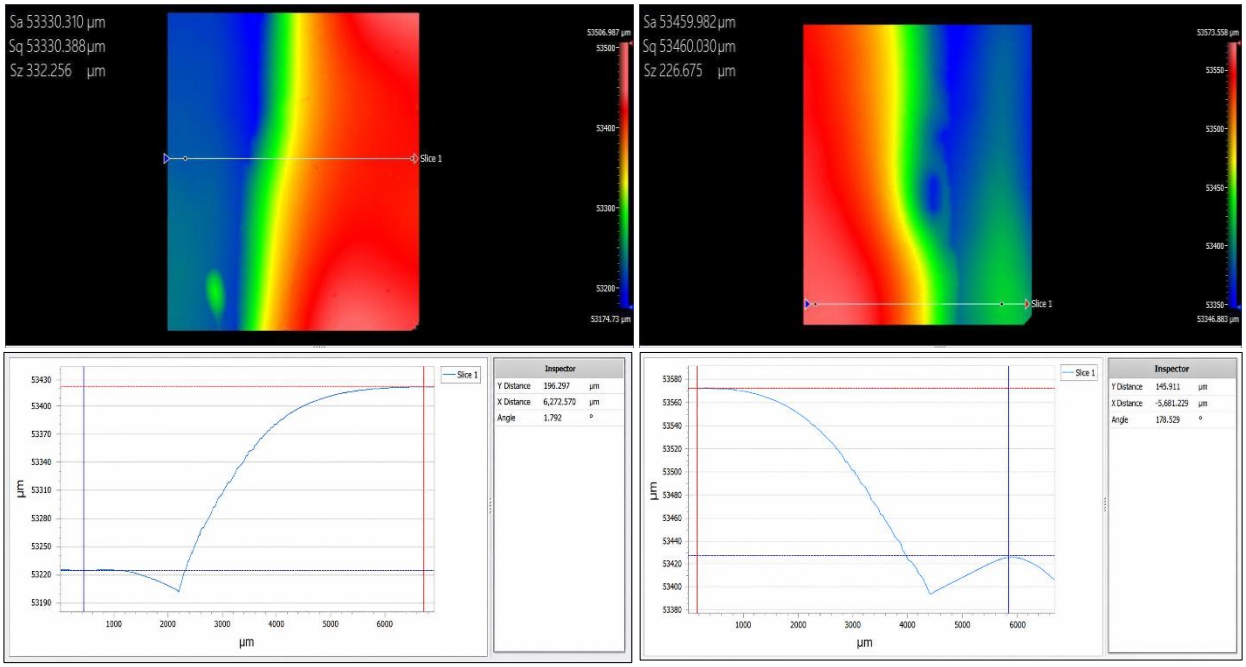

Figure 4. Dry film thickness of primer (left) and topcoat (right)

The temperature inside the fume cupboard where spraying was performed was recorded at 22.7 °C ± 1.5 °C, and relative humidity was 40 % ± 8%. At these conditions, the primer and topcoat (Penguard FC) were found to dry to a "touch-dry" state (i.e., the state of drying when slight pressure with a finger does not leave an imprint or reveal tackiness) after approximately 4 hours and 2.5 hours, respectively. The hydrophobic particle suspension in ethanol (2% w/w), produced by spraying application, was qualitatively evaluated for various conditions. Firstly, it was found that ethanol does not markedly result in swelling of the dry topcoat which would allow for particles to adhere to the surface. For this reason, spraying (distance 20 cm; flow rate 600 mL/min) was applied at different drying times from the initial application of the topcoat to determine whether particles would adhere to the surface of semi-dry film. Upon spraying and evaporation of ethanol from the sample surface, qualitative assessment in terms of adhesion, hydrophobicity, and homogeneity allowed to establish that at the aforementioned conditions the optimal drying time of the topcoat prior to spraying application of hydrophobic particle suspension is approximately 2.5 hours, which agrees with the supplied technical manual containing drying times for "surface touch dry" state, see Figure 5.

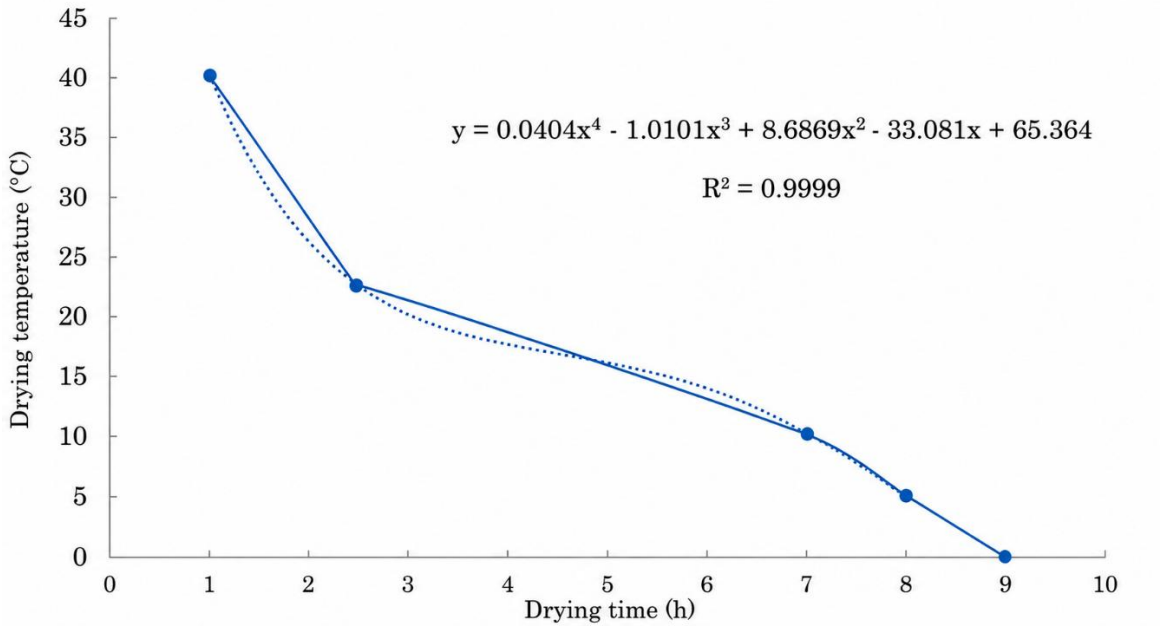

Figure 5. Drying time of topcoat to a surface touch dry state

Moreover, it was found that if the spraying is conducted before a critical drying time (i.e., below 2 hours period from topcoat application), the excess of ethanol was found to yield formation of cracks on the topcoat film upon drying, which were also not homogeneously filled with hydrophobic particles. This may lead to higher corrosion rates relative to treated metal sheets without such surface defects. On the other hand, if the drying is prolonged to 3.5 hours or longer, the extent of particle adhesion onto the topcoat significantly reduces. Considering potential differences in the spraying environment (e.g., temperature) for commercial applications, Fig. 5 shows the drying time for a different set of temperatures (data points extracted from Penguard FC technical manual). Using the plot, or 4th order polynomial fit ($R^2 = 0.99$), the corresponding drying time for "surface touch dry" state can be extrapolated for a required temperature.

Results and Discussion

Evaluation of Surface Hydrophobicity

Hydrophobicity of applied coatings was evaluated using sessile drop method (DSA25 Drop Shape Analyzer). Ultra-pure deionized water (< 18 MΩ.cm) was used to form sessile droplets of 100-200 μL. The drops were imaged through a video camera and the contact angle (on both sides of the drop) was determined automatically through the software of the instrument. Measurements of contact angle of sprayed metal samples with different combinations of hydrophobic particle sizes were performed at various locations for random samples (see Table 3). Measurements were performed in 15 to 20 different locations for each metal sample and for five independent metal

samples; the standard deviation was calculated based on these measurements. The largest contact angle, i.e., 140° was found for a particle mixture containing 75% of 250 nm and 25% of 800 nm particles. Smallest size particles (250 nm) offer second to best hydrophobic performance (also ~140°) likely caused by the formation of denser surface structures upon drying relative to the larger particles (800 nm). Those particles resulted in contact angle of 137°. A 50/50% combination led to lowest contact angle measured, i.e., 136°. The measured contact angle of the untreated topcoat with hydrophobic particles is below 90° (i.e., hydrophilic). No noticeable difference in the spraying process was observed among the four particle size combinations.

Table 3. Contact angle measurements of hydrophobic surfaces prepared using mixtures of small (~250 nm) and large (~800 nm) silica particles

Hydrophobic particle composition (% w/w)	Sample 1 (°)	Sample 2 (°)	Sample 3 (°)	Average (°)	Standard deviation (°)
100% 250 nm	137.7	140.4	141.4	139.8	1.6
100% 800 nm	135.1	136.9	137.9	136.6	1.2
50% 250 nm / 50% 800 nm	133.7	136.5	137.1	135.8	1.5
75% 250 nm / 25% 800 nm	139.1	140.5	141.2	140.3	0.9
Topcoat (0% particles)	78.3	88.0	83.2	83.2	4.0

Evaluation of Surface Morphology

Firstly, samples with topcoat only (absence of hydrophobic particles) were analysed. In the Figure 6a a magnified image of the surface reveals defects in coatings in the form of pores with diameters <1 mm. Optical micrographs, shown in Figure 6b, reveal the pore size range between 33 µm and 220 µm. The most likely cause for such defects is the air entrainment during the high-speed spraying procedure. The high aspect ratio surfaces (i.e., edges) were found to be covered with non-uniform coating (Fig. 6c). Dripping of the excess coating is also observed at the edges particularly at the corners of the square samples. Such variation in thickness may result in ineffective coating properties for a metal surface, being either below or above the recommended thickness notified by the supplier.

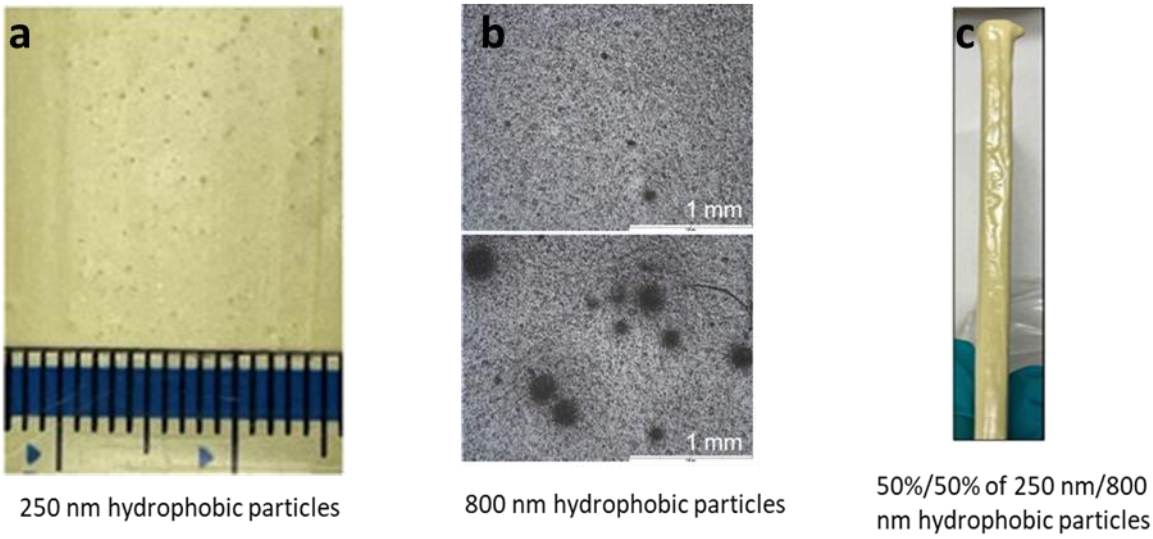

Figure 6. Contact angle measurements of metal sheets sprayed with selected combinations of hydrophobic particle mixtures.

Samples with topcoat only were further analysed using SEM. From Figure 7 it is observed that the dried topcoat layer forms a nearly continuous surface with occasional surface defects. These defects appear as non-uniform holes (possibly micro-pores) through the bulk varying in size (typically <10 µm), which reveals complex structure of the bulk interior and potential pathways against intended metal surface protection.

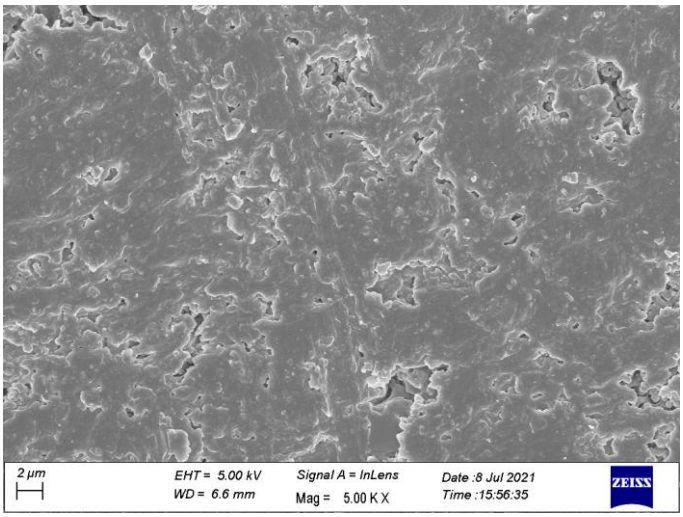

Figure 7. SEM showing surface morphology of topcoat without hydrophobic particles

Qualitative study for adhesion and surface hydrophobicity showed that the treated surfaces with hydrophobic particle suspension require at least 24 hours of drying time, and for best results 48 hours. Below these drying times it was found that the deposited water droplets on the treated surfaces have contact angles of less than 90˚ with rapid spreading of water drop. The final dried

samples overall appear to have a homogeneous layer of hydrophobic particles (Figure 8). Some areas were found to be only partly covered with hydrophobic particles particularly at the edges. Spraying the edges of the metal sheets was found to be not very effective in terms of particle deposition because of the strong spraying stream of the particle/ethanol suspension, which did not sustain on the surface but flowed off vertically down over the main surface. In addition, some areas, particularly close to the edges, are seen to have higher particle concentration than the others. This was probably caused by the uneven volume of particle/ethanol suspension sprayed, which at places accumulated into droplets instead of a thin film, and upon evaporation ethanol droplets contracted resulting in locally higher particle concentration. Generally, it was found that spraying of 2% w/w particles in ethanol suspension required a repeated application of up to 10 times, where post each spraying application ethanol is required to evaporate for the particle to adhere to the surface of the topcoat. An alternative particle concentration of approximately 20% w/w in ethanol was tested, which showed that only up to two spraying applications were required to cover the topcoat surface evenly with chosen hydrophobic particles. Since the spraying system can handle such concentration for a prolonged time prior to cleaning, it may substantially reduce overall spraying process time and improve productivity. Upon measurement of contact angles at different locations of all samples with hydrophobic particle coating it was found that the hydrophobicity was varying between ~ 9° and ~ 130°, in agreement with qualitative observations on homogeneity of the coating. Areas of varying hydrophobicity were marked and further analysed using SEM. In locations with low contact angles (90°), hydrophobic particles are found to form agglomerates and clusters potentially being partially covered in the topcoat material (Figure 9). Some particles were observed to be embedded in the bulk topcoat. Only a small fraction of the treated area is covered by hydrophobic particles that would increase hydrophobicity.

Figure 8. Photograph of fully treated metal sheet with 100% of 800 nm hydrophobic particles (~ 48 h of drying of hydrophobic coating)

In these circumstances, it is important to note that the contact angle is still above the value of samples with topcoat only, yet, is delivering very limited required enhanced material properties. Those areas that have contact angles of 130° and above are measured to have homogeneous coverage by hydrophobic particles as evidenced using SEM images (Fig. 10). From this, one can also see that an insignificant proportion of particles is also embedded in the topcoat layer and some formation of agglomerates, yet delivering required material properties in terms of hydrophobicity. Such differences may have occurred because of a marginally uneven topcoat film thickness throughout the surface, producing variable areas of dryness. In turn, spraying of ethanol/particle suspension under the given conditions resulted in higher interaction with the topcoat film. Spraying edges of the metal sheets was found to be not very effective in terms of particle deposition because of the strong spraying stream of the particle/ethanol suspension.

This did not sustain on the surface but flowed off vertically down over the main surface. In addition, some areas, particularly close to the edges, are seen to have higher particle concentration than the others. This was probably caused by the uneven volume of particle/ethanol suspension sprayed, which at places accumulated into droplets instead of a thin film. Upon evaporation ethanol droplets contracted, resulting in locally higher concentration. So, on edges it was difficult to meet homogeneous film thickness. The spraying of hydrophobic particles was also found rather ineffective in these areas. Figure 11 below shows that the area close to the edge and the sides has poor hydrophobic particle distribution. Such configuration along with non-homogeneous primer and topcoat film thickness leaves the edges and side surfaces most vulnerable to potential damages that may be prone to more rapid corrosion.

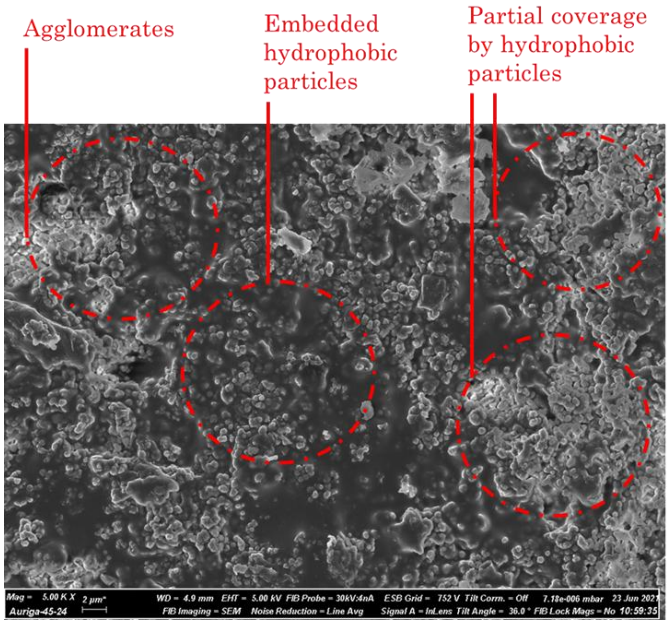

Figure 9. Surface morphology using SEM for surfaces with sessile drop contact angle ~90°

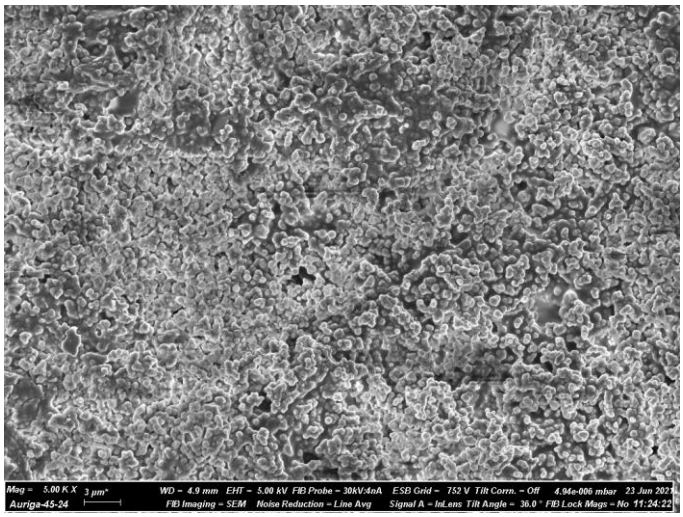
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Figure 10. Surface morphology using SEM for surfaces with sessile drop contact angle ~125°

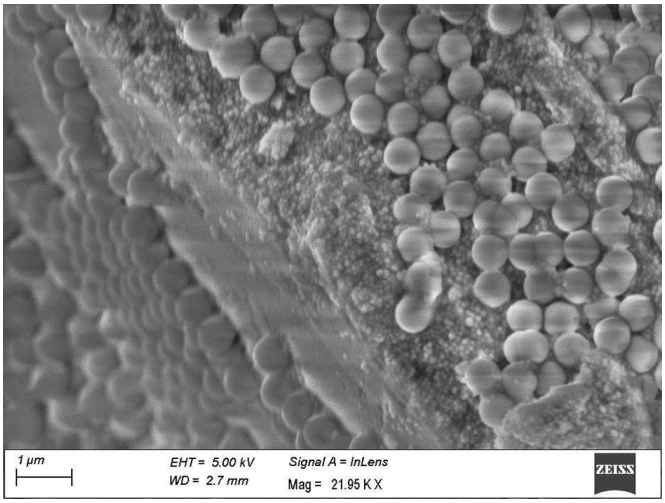

Figure 11. Surface morphology using SEM for surfaces at the edge of coating with hydrophobic particles

Conclusions and future work

Mild steel samples have been prepared according to relevant BS and ISO standards. The required surface roughness was validated using an optical interferometer. Using a spraying system two coatings of required thickness were applied consisting of primer and topcoat. Surface morphology of thick dried topcoat layer is observed to form a nearly continuous surface with occasional surface defects i.e., micropores that range in size between several to hundreds of micrometres. Four different combinations of synthesized hydrophobic particles,

consisting of 250 nm and/or 800 nm, were applied to a semi-dry topcoat film to allow for particle adhesion with an aim to create a hydrophobic surface layer. SEM analysis has shown that in areas

with low contact angle (90), hydrophobic particles are found to form large agglomerates and clusters, which are probably embedded/covered in the topcoat fluid itself.

In areas with high contact angle (>130°) hydrophobic particles are found to be partially embedded and covered across the whole topcoat surface with little to no agglomeration. A vast area at the edges of treated samples was found to contain very few hydrophobic particles, suggesting that particle application by spraying was inefficient. Best performing hydrophobic particles in terms of contact angles were found for 100% of 250 nm size and a combination of 75%: 25% of 250 nm and 800 nm, both delivering hydrophobic coating with ~40° contact angles.

This study demonstrates a straightforward method for developing hydrophobic coatings and future research is advisable to evaluate the performance of these coatings and their chemical stability including the bonding between silica particles and the polymeric matrix and assessing corrosion

durability under real-world conditions. The catastrophic failures in critical assets like oil and gas platforms can lead to devastating outcomes, including multiple fatalities, massive property damage, and total facility loss. These incidents often result in large-scale environmental harm, such as significant oil spills or toxic releases that require full evacuations, alongside severe operational delays and long-term economic disruptions to national infrastructure and government functions.

These epoxy hydrophobic coatings are expected to deliver significant socio-economic benefits, including reduced maintenance costs, enhanced energy efficiency, and extended asset lifespan. Ultimately, this research aims to evaluate the efficiency of these potential protective treatments to validate their suitability for practical applications, thereby integrating sustainability criteria to drive innovation within the oil and gas industry. In addition, the findings of this study open the door to explore the benefits of these hydrophobic coatings for a new generation of nanocomposites with advanced functional properties.

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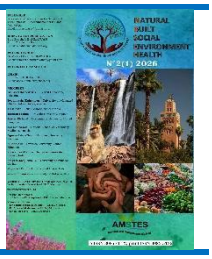

Microalgae-Based Bioremediation of Microplastic-Contaminated Industrial Wastewater: Mechanisms and Challenges

Yasmine Khalki [1,a], Selma Siham El Khayat [1,2,b], Ghita Radi Benjelloun [1,c], Alla Silkina [3,d], Bouchaib Bahlaouan [4,e], Nadia Boutaleb [1,f*]

[1] *Hassan II University of Casablanca, Laboratory of Biotechnology, Agri-Food, Materials and Environment, Team: Biotechnologies, Resource Valorization, Quality, Health and Ecotoxicology, Faculty of Science and Technology Mohammedia, BP 146, Mohammedia 20650, Morocco*

[2] *Nephrology Department, UHC Ibn Rochd, Faculty of Medicine and Pharmacy, Hassan II University of Casablanca, Morocco*

[3] *Algal Research Group, Department of Biosciences, Swansea University, Singleton Park, Swansea, Wales SA28PP, United Kingdom*

[4] *Higher Institutes of Nursing and Health Technical Professions (ISPITS) , Laboratory of Care, Health and Sustainable Development 2S2D, Casablanca 22500, Morocco*

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[a] ***ORCID:*** *0009-0000-3479-0723*; ***Email***: yasmine.khalki@etu.fstm.ac.ma

[b] ***ORCID:*** *0000-0003-4746-7516*; ***Email***: selmasiham@yahoo.fr

[c] ***ORCID:*** *0000-0002-9884-8119*; ***Email*** : ghita.radibenjelloun@etu.fstm.ac.ma

[d] ***ORCID:*** *0000-0002-1804-8083*; ***Email***: a.silkina@swansea.ac.uk

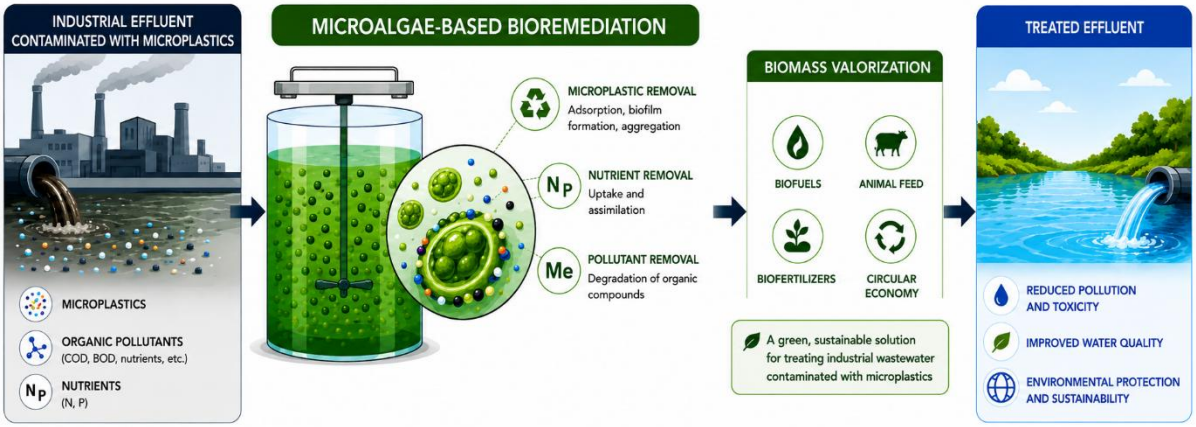
[e] ***ORCID:*** *0000-0002-0976-1274*; **Email**: b.bahlaouan@ispitscasa.ac.ma

[f] ***ORCID***: *0000-0003-1628-4311*; **Email:** nadia.boutaleb@fstm.ac.ma

* ***Corresponding author:*** Nadia Boutaleb; ***Email***: nadia.boutaleb@fstm.ac.ma

Graphical Abstract

The integration of microalgae into various industrial wastewater treatment systems is an environment-friendly bioremediation strategy against both organic pollution and microplastic contamination. Following treatment, the resulting biomass offers multiple opportunities for valorization, particularly in the production of biofuels, biofertilizers, and animal feed. Their use fits perfectly within a sustainable and circular economy approach.



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Abstract: Microalgae-based bioremediation presents a promising eco-friendly approach for removing microplastics (MPs) from industrial effluents. This review summarizes the current understanding on this subject. The article begins by describing the characteristics and origins of MPs in industrial discharges. It then reviews documented mechanisms of microalgae–MP interactions, including adsorption/biosorption, bioflocculation, accumulation, and partial degradation. Important environmental and operational factors that influence treatment efficiency—such as MP size and charge, algal species, and culture conditions—are analysed. Additionally, the article discusses analytical methods necessary for MP characterization and monitoring performance. Microalgae-based methods are contrasted with traditional physical and chemical processes, highlighting the potential value of the processed biomass (such as bioenergy and biofertilizers) to showcase a circular bioeconomy approach. The review concludes by pinpointing key research gaps and offering recommendations for standardizing experimental procedures and encouraging the adoption of microalgal systems within sustainable wastewater treatment strategies.

Keywords: *Microplastic removal, Microalgae, Wastewater treatment, Biodegradation.*

Introduction

Among the major environmental problems of the twenty-first century is microplastic pollution. Most of these particles reach aquatic ecosystems through industrial effluents [1]. Conventional wastewater treatment technologies, such as coagulation, filtration, and biological processes, do not show very effective results in removing small particles measuring less than ten micrometres [2]. Moreover, they often produce secondary sludge, the treatment of which is very costly. Because of these limitations, it has become essential to look for other solutions that are more effective, more sustainable, and more cost-effective.

Among the emerging solutions, the use of microalgae-based systems is attracting growing interest because of their multifunctional role in wastewater treatment. Microalgae can interact with microplastics through physico-chemical adsorption on the cell surface, as well as on extracellular polymeric substances (EPS), promoting bioflocculation, which potentially contributes to the partial degradation of the polymers [1].

At the same time, microalgae make it possible to recover nutrients and produce biomass. This helps create treatment strategies based on the circular economy [2]. But, their large-scale use, such as at the industrial scale, remains limited for several reasons, such as the toxicity caused by microplastics, the time required for treatment, and the difficulty of separating microalgae–microplastic aggregates in order to valorize them afterwards [3,4].

Microplastics are plastic particles measuring less than five millimetres that come from two distinct types of sources. First, primary sources, such as microbeads and synthetic fibres; or secondary degradation of larger-sized plastics [5]. They present different morphologies and can appear in the environment in the form of fibres, fragments, films, or spheres, etc. They are composed of several polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) [6,7] (Fig. 1). Their environmental behaviour depends largely on their physicochemical properties, such as size, density, and surface charge. These properties also influence the way they interact with microalgal cells [8,9]. This is the reason why these characteristics are very important for improving biological treatment strategies [10].

Industrial effluents are an important source of microplastics in water, especially those coming from the textile, plastic, cosmetics, pharmaceutical, and food-processing industries [11]. During certain operations, such as synthetic fibre washing, plastic manufacturing, or cosmetic

formulation, microplastics are released into wastewater [12]. During certain operations, such as synthetic fibre washing, plastic manufacturing, or cosmetic formulation, microplastics are released into wastewater [13].

In addition to their presence in the environment, microplastics have important effects on microalgae, these essential organisms in natural and engineered aquatic environments [14,15]. Being exposed to microplastics can cause oxidative stress, reduce the efficiency of photosynthesis, and also affect the growth of microalgae [16]. Moreover, when microplastics and microalgae interact with each other, this can change the aggregation and sedimentation processes, as well as the nutrient cycle in aquatic ecosystems [17]. It is thus very important to understand the interactions between these small particles and these microorganisms, with the aim of improving the biological treatment of wastewater and making it more effective under real industrial conditions [15].

Figure 1. Major plastic polymers and their common applications contributing to microplastic pollution.

Microalgae-Based Bioremediation: Concept and Mechanisms

General Concept of Microalgal Bioremediation

The application of microalgae for bioremediation has gained attention as a sustainable and green strategy for treating industrial effluents polluted with microplastics. Microalgae are able to remove pollutants while producing biomass that can be valorized for bioenergy, biofertilizers, or bioproducts [18]. This double function makes them particularly interesting for integrated circular wastewater treatment systems. Moreover, microalgae represent a biological platform for the capture of microplastics through physicochemical interactions and aggregation, which could potentially reduce the concentration of MPs in the treated waters below the levels expected by conventional methods.

Mechanisms of Interaction Between Microalgae and Microplastics

Microalgae interact with microplastics through multiple mechanisms:

Adsorption/Biosorption: Microplastics adsorb on the surface of algal cells or extracellular polymeric substances (EPS) to form stable aggregates. The EPS secreted by the algae enhances the ability to bind with various types of polymers [19].

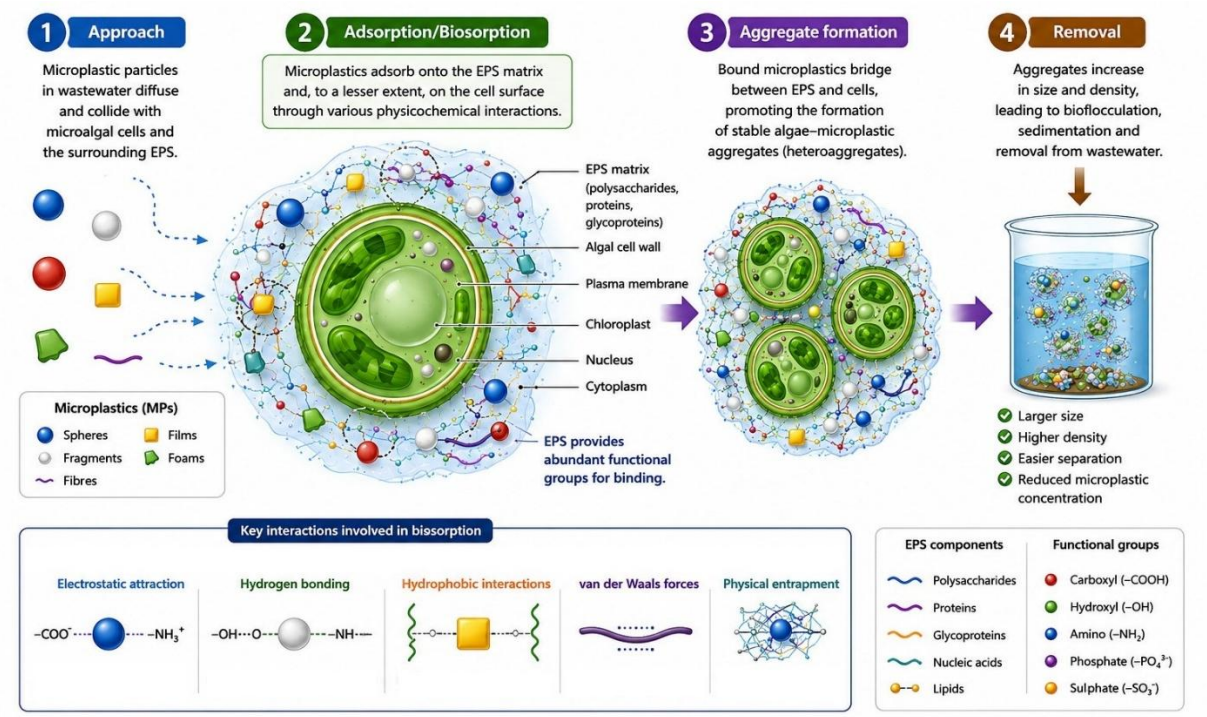

Figure 2. Schematic representation of microplastic adsorption/biosorption by microalgae and subsequent bioflocculation-mediated removal.

Bioflocculation: microplastics adhere to algal cells, promoting sedimentation and removal from the aqueous phase. The efficiency of bioflocculation depends on the algal species, the type of microplastics and environmental conditions [19,20] (Fig. 3).

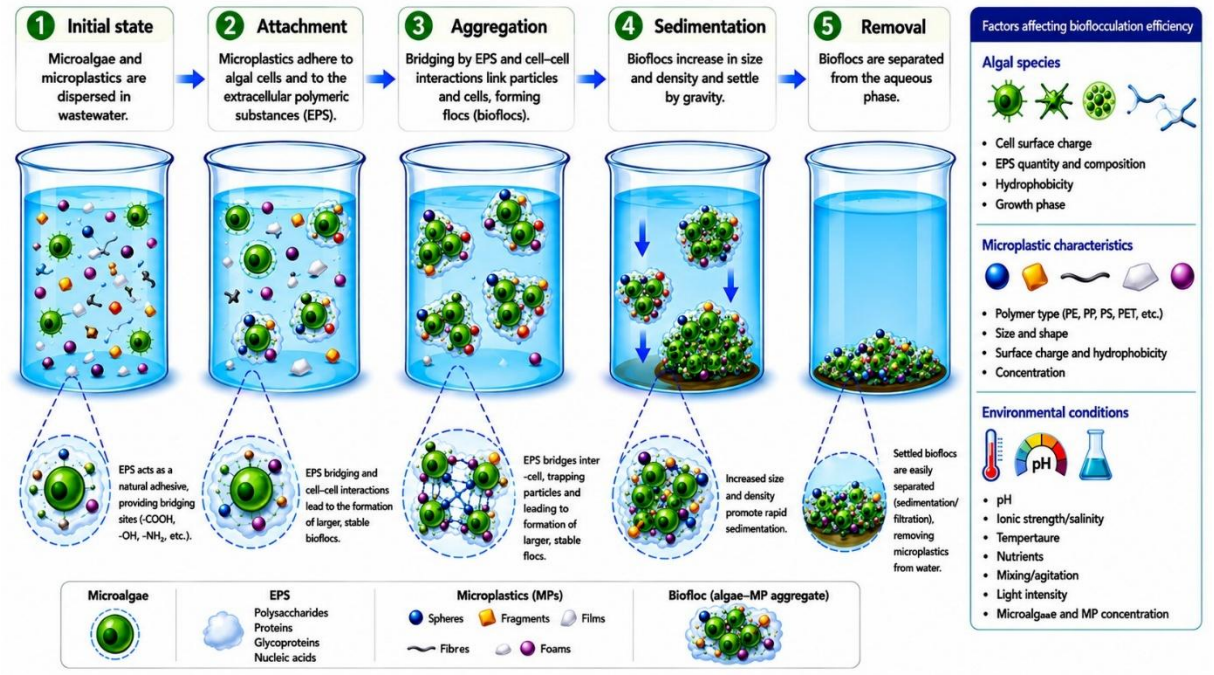

Figure 3. Schematic representation of EPS-mediated bioflocculation, sedimentation, and removal of microplastics by microalgae.

Bioaccumulation and Partial Biodegradation: ingestion of small microplastics and their partial degradation through enzymatic or oxidative processes. Polymers are only degraded to a limited extent, and these interactions contribute to reducing their persistence in the environment [21,22] (Fig. 4).

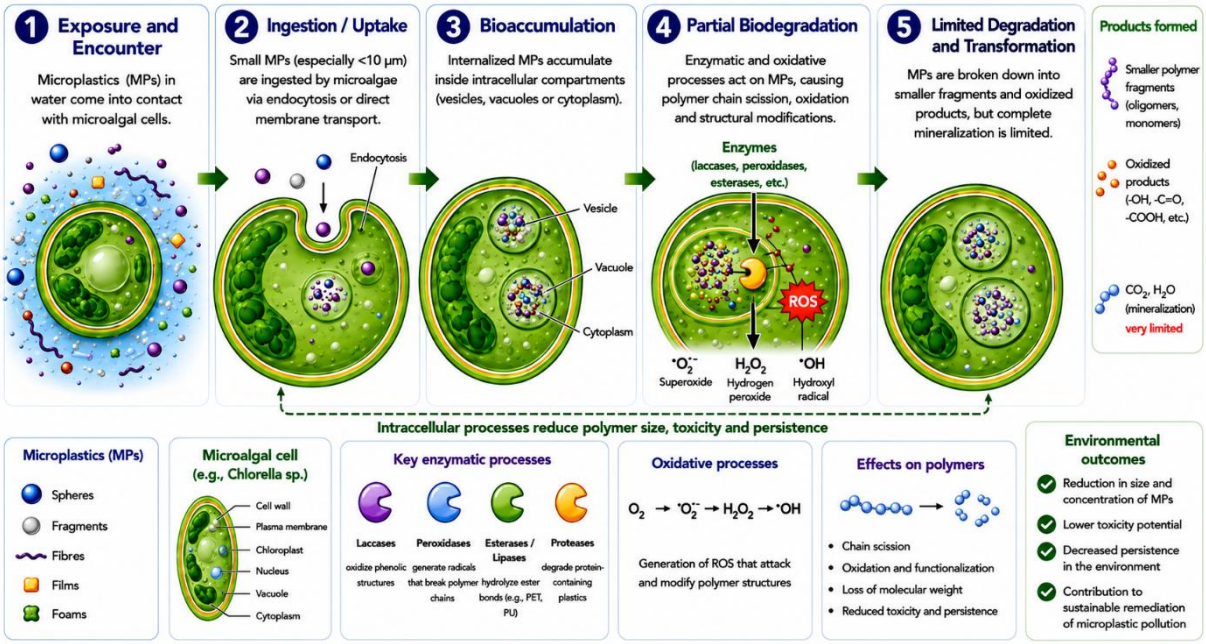

Figure 4. Schematic representation of microplastic bioaccumulation, partial biodegradation, and transformation by microalgae.

Photobiological Effects: Photosynthesis in microalgae can lead to the oxidative transformation of adsorbed microparticles and thus further contribute to bioremediation [19,23] (Fig. 5).

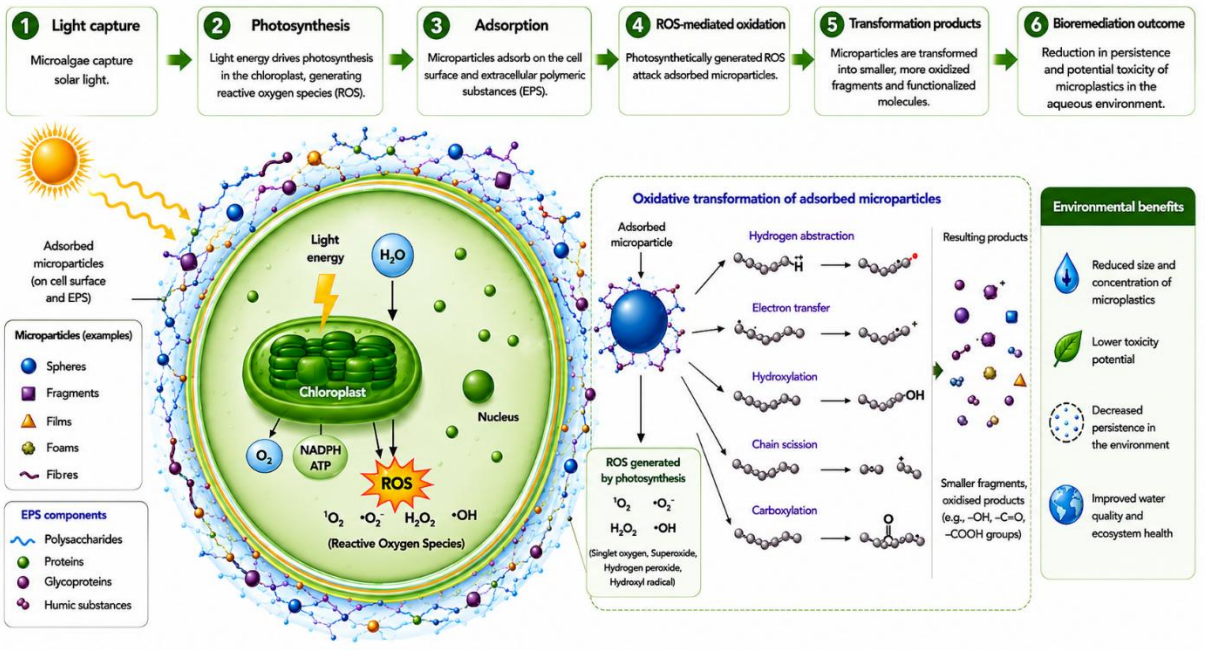

Figure 5. Schematic representation of photobiological oxidation and transformation of microplastics by microalgae.

Table 1. Comparative Analysis of Microalgal Species and their Mechanisms for Microplastic Capture and Removal.

Microalgae species	**Type of microalgae**	**MPS (s)**	**source of microplastic**	**interaction / mechanism**	**Ref.**
Chlorella vulgaris	Green microalga (Chlorophyta)	(PE), (PS), (PP)	Industrial packaging waste, cosmetics, textile industries, domestic wastewater	Strong biosorption through extracellular polymeric substances (EPS); bioflocculation and aggregation of MPs with algal biomass	[24]
Scenedesmus obliquus	Freshwater green microalga	Polystyrene microbeads, PE fragments	Plastic manufacturing effluents, industrial wastewater	Adsorption onto cell surface; formation of hetero-aggregates; oxidative stress-induced transformation of MPs	[25]
Spirulina platensis	Cyanobacterium (blue-green microalga)	(PE), Polyamide fibres	Textile wastewater, cosmetic residues	Bioflocculation and biosorption mediated by polysaccharides and protein-rich cell wall	[26]
Haematococcus pluvialis	Freshwater green microalga	Nanoplastics and PS particles	Industrial plastic degradation products	Surface adsorption and oxidative photobiological transformation under light exposure	[27]
Nannochloropsis oculata	Marine microalga	(PET),PS nanoparticles	Marine industrial discharges and aquaculture activities	EPS-mediated adsorption and sedimentation enhancement	[28]
Dunaliella salina	Halophilic green microalga	PS and PE microplastics	Saline industrial wastewater and desalination rejects	Bioaccumulation of nanosized plastics and antioxidant-mediated stress response	[29]
Chlamydomonas reinhardtii	Unicellular green microalga	Polystyrene nanoplastics	Laboratory and industrial plastic residues	Internalization of nanoplastics, oxidative stress response, partial biodegradation potential	[30]
Skeletonema costatum	Marine diatom	PE and PS particles	Coastal industrial discharge and port / harbour pollution	Adsorption on silica-rich frustules and aggregation with suspended particles	[31]

Factors Affecting Bioremediation Efficiency

Several factors influence the efficiency of microalgae-based bioremediation:

Table 2. Main factors affecting the interaction between microalgae and microplastics during bioremediation.

Factor	Description
Microplastic properties	Size, shape, polymer type, and surface charge influence adsorption and aggregation.[32,33]
Algal species	Microalgae such as Scenedesmus obliquus, Chlorella vulgaris, and Spirulina platensis show variable EPS production, growth rates, and tolerance to microplastics [1,2].
Environmental conditions	Light intensity, temperature, pH, and nutrient availability strongly affect algal growth and interaction with microplastics [2,34].
Exposure time	Sufficient contact time is required to allow adsorption, aggregation, and partial degradation [35].

Industrial Effluents as a Matrix for Bioremediation

Physico-Chemical Complexity of Industrial Wastewaters

Industrial effluents are complex matrices containing microplastics, heavy metals, dyes, surfactants, and nutrients that may influence the effectiveness of microalgae-based bioremediation [36]. Co-contaminants may promote or inhibit microalgal growth and the removal of microplastics. For example, certain heavy metals can cause stress, thereby reducing the photosynthetic efficiency of the algae. Certain nutrients can promote biomass productivity and the release of extracellular polysaccharides (EPS), which may facilitate the adsorption and flocculation of microplastics. Consequently, knowledge of the chemical and physical properties of effluents is essential for selecting suitable algal species and optimizing treatment conditions [38].

Adaptability of Microalgae to Industrial Effluents

Microalgae exhibit varying degrees of tolerance to industrial effluent toxicity, which is critical for successful bioremediation [36]. Some species, such as *Scenedesmus obliquus* and *Chlorella vulgaris*, can survive and grow in high-strength effluents, maintaining their ability to adsorb MPs and produce EPS [37]. Adaptive mechanisms include adjustment of photosynthetic

activity, enhanced EPS secretion, and activation of antioxidant defences to mitigate oxidative stress caused by contaminants [38]. These properties make microalgae versatile candidates for the treatment of diverse industrial effluents [39].

Implications for Bioremediation Performance

The complexity of industrial effluents directly affects the removal efficiency of microplastics [40]. High concentrations of co-contaminants can compete for adsorption sites on algal cells or interfere with bioflocculation processes [41]. Conversely, the presence of nutrients may stimulate algal growth, increase EPS production, and enhance MP aggregation and sedimentation [42]. Pilot studies have demonstrated that tailoring operational parameters—such as dilution, aeration, and residence time—can mitigate inhibitory effects and maximize MP removal [43]. Understanding the matrix-specific challenges is therefore essential for designing scalable microalgae-based wastewater treatment systems.

Experimental Strategies and Technological Approaches

Laboratory-Scale Studies

Laboratory-scale experiments provide controlled conditions to investigate microalgae–microplastic interactions and optimize operational parameters [44]. Batch and continuous cultures are commonly used to evaluate the adsorption, bioflocculation, and partial biodegradation of MPs by different algal species [45]. Variables such as light intensity, temperature, pH, nutrient concentration, and microplastic characteristics are systematically tested to determine the optimal conditions for maximal MP removal [46]. These studies form the foundation for understanding the underlying mechanisms and provide essential data for scaling up to pilot or industrial systems [47].

Pilot and Industrial-Scale Systems

To apply microalgae-based bioremediation on a large scale, pilot and industrial systems are needed. They must maintain good treatment efficiency without making costs explode. Photobioreactors, open ponds, or hybrid systems combining microalgae with filtration or biochar are often used [48]. On a large scale, several difficulties appear: light must be

distributed evenly, nutrient levels must be controlled, enough time must be allowed for microalgae to remove microplastics, and finally, biomass must be harvested efficiently while consuming as little energy as possible [49].

Analytical Methods for Monitoring Microplastic Removal

Accurate monitoring of MP removal is essential [50]. It also helps to characterize algal performance properly. To identify polymers, two techniques are mainly used: Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy. Scanning electron microscopy (SEM) is used to observe surface morphology [51,52]. As for algal biomass and EPS production, they are typically measured through chlorophyll content, dry weight, and various biochemical assays [50,51]. These methods provide both quantitative and qualitative data. They allow researchers to evaluate treatment efficiency and to understand the removal mechanisms.

Advantages, Limitations, and Challenges

Advantages of Microalgae-Based Bioremediation

The use of microalgae in bioremediation can offer several ecological and operational advantages, as it is a sustainable and environmentally friendly technique that helps reduce reliance on chemical treatments [55]. Second, microalgae, having the capacity to remove microplastics and nutrients simultaneously, prevent eutrophication and improve water quality [56]. Third, the generated biomass can be be valorized into biofertilizers, bioenergy, or other bioproducts, thus integrating the process into a circular economy logic [57]. Moreover, microalgae-based systems can adapt to different types of industrial effluents, offering wide versatility along with great scalability.

Limitations

Despite its advantages, microalgae-based bioremediation also has its limits. When there are too many microplastics, or other pollutants such as heavy metals, dyes, or surfactants, the microalgae grow less well. This reduces EPS production and makes the treatment less effective [58]. In general, plastics are never completely degraded. Separating microplastics from algal biomass before valorization also remains difficult. Finally, growing microalgae on a large scale

requires careful control of the surrounding conditions—light, temperature, and pH—as well as fairly intensive operational management to maintain good performance [59].

Challenges and Research Gaps

Major challenges to implementing microalgae-based systems at the industrial scale include standardizing protocols for MP removal, developing reliable monitoring methods, and assessing the long-term ecotoxicological effects of MPs on algal populations [60]. Further research is needed to optimize species selection, improve biomass harvesting techniques, enhance MP adsorption and flocculation, and evaluate the feasibility of integrating these systems into existing wastewater treatment infrastructure [61]. These gaps must be bridged before successful laboratory studies can be translated into industrial use.

Conclusion

Bioremediation based on the use of microalgae is a promising, cost-effective, and sustainable method for treating industrial effluents contaminated by small microplastic particles. Thanks to several mechanisms, such as adsorption, bioflocculation, and partial degradation, microalgae manage to reduce the amount of microplastics present in effluents, while retaining the ability to capture nutrients and produce biomass that can be reused. Laboratory studies have shown that several species, such as *Scenedesmus obliquus*, *Chlorella vulgaris*, and *Spirulina platensis*, can have this property of adaptation to complex industrial effluents and remain effective even when experimental conditions change. Challenges still remain to be understood and resolved, such as the incomplete degradation of polymers, the negative effects of other pollutants present in the effluent, and the difficulty of separating these MP aggregates from the algal biomass before valorizing it. Future research should focus more on the choice of the best algal species used, the combination of microalgae with other biotechnologies, the creation of standardized experimental protocols, and the study of feasibility at the industrial scale. By following all these principles of the circular economy and sustainability policy, new efficient, eco-friendly, and, of course, cost-effective solutions could thus be implemented to reduce this pollution by these dangerous microparticles in industrial effluents. Future research should prioritize the integration of microalgae with complementary biotechnologies, such as bacterial consortia, enzymes, or biofilms, to enhance microplastic removal efficiency and overall treatment

performance. Additionally, adopting circular economy approaches through biomass valorization (biofertilizers, bioenergy, or bioproducts), standardizing experimental protocols, and implementing life cycle and techno-economic assessments will be essential to promote sustainable industrial applications. By addressing these challenges, microalgae-based bioremediation can be developed into a reliable and eco-friendly solution for mitigating microplastic pollution in industrial effluents.

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Ethics Approval
Not applicable. This review article did not include human participants, animals, or clinical data

Data Availability
No datasets were generated or analysed during the current study.

Code Availability
Not applicable. No code or software was developed or analysed during this study.

Conflict of Interest
The authors declare that they have no conflict of interest.

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Marantaceae of the Tropical Rainforests of Central Africa: Multi-purpose Plants of Hidden Harvests

Ichida Pherla Oyanadigui Odjogui [1a*], Christian Moupela [1b], Aurélien Mokea Niaty [2c], Rolf Gaël Mabicka Obame [3d]

[1] *University of Science and Technology of Masuku, National Institute of Agronomy and Biotechnology, Department of Phytotechnology, plant biotechnology and protection Laboratory, PO Box 941 Franceville, Gabon*

[2] *University of Science and Technology of Masuku, Department of Biology, Faculty of Science, P.O. Box 941, Franceville, Gabon*

[3] *University of Science and Technology of Masuku, National Institute of Agronomy and Biotechnology, Department of Phytotechnology, Soil and Environmental Analysis Laboratory, PO Box 941 Franceville, Gabon*

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[a] ***ORCID:*** *0009-0003-6423-7197*; ***Email***: *odjogui@gmail.com*

[b] ***ORCID:*** *0009-0007-5617-9440*; ***Email***: *cmoupela@yahoo.fr*

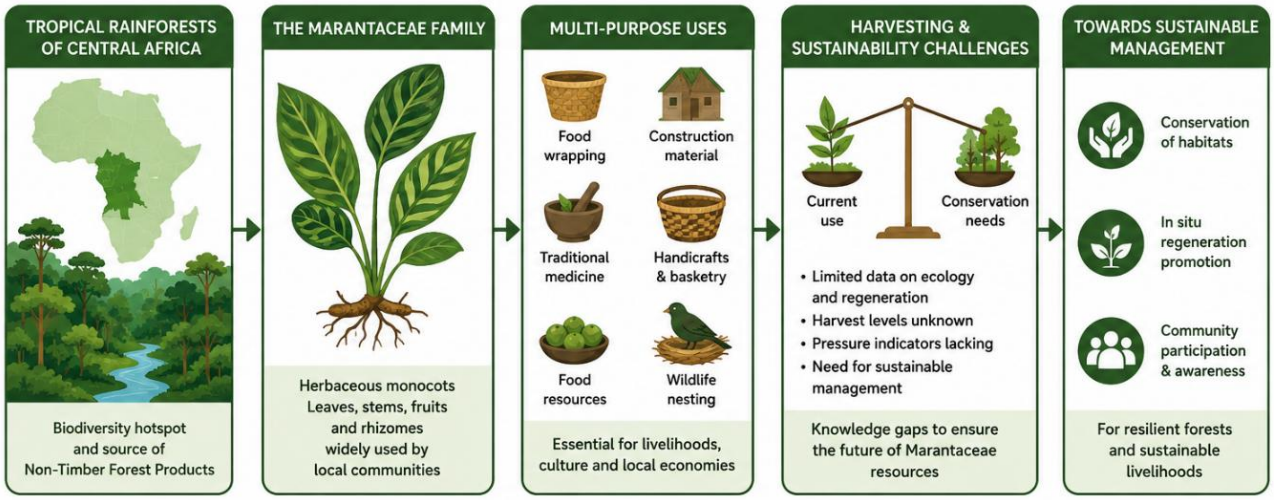
[c] ***ORCID:*** *0009-0000-2300-8724*; ***Email***: *amokeaniaty@yahoo.fr*

[d] ***ORCID***: *0000-0002-8519-1170*; ***Email***: *rolfgaelmabickaobame@gmail.com*

* ***Corresponding author***: Oyanadigui Odjogui Ichida Pherla; ***Email***: odjogui@gmail.com

Graphical Abstract

The tropical rainforests of Central Africa harbour highly valued Non-Timber Forest Products (NTFPs). Among these, the family Marantaceae is prominent because of the multiple uses of its leaves, stems, fruits and rhizomes by rural communities. This bibliographic synthesis summarizes the available knowledge on the geographical distribution, botanical and economic characteristics, and ethnobotanical importance of Marantaceae in Central Africa. It also highlights important knowledge gaps concerning the ecology, reproductive biology, harvesting pressure and regeneration potential of exploited species, emphasizing the need for further research to support their sustainable management.


TROPICAL RAINFORESTS OF CENTRAL AFRICA
Biodiversity hotspot and source of Non-Timber Forest Products
THE MARANTACEAE FAMILY
Herbaceous monocots Leaves, stems, fruits and rhizomes widely used by local communities
MULTI-PURPOSE USES
Food wrapping
Construction material
Traditional medicine
Handicrafts & basketry
Food resources
Wildlife nesting
Essential for livelihoods, culture and local economies
HARVESTING & SUSTAINABILITY CHALLENGES
Current use
Conservation needs
• Limited data on ecology and regeneration
• Harvest levels unknown
• Pressure indicators lacking
• Need for sustainable management
Knowledge gaps to ensure the future of Marantaceae resources
TOWARDS SUSTAINABLE MANAGEMENT
Conservation of habitats
In situ regeneration promotion
Community participation & awareness
For resilient forests and sustainable livelihoods

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Abstract: The tropical rainforests of Central Africa harbour highly valued Non-Timber Forest Products (NTFPs) that are widely used by rural communities. These products are essential to the socio-economic, cultural and dietary life of households and represent an important source of income. Among these NTFPs, the family *Marantaceae* is prominent. It is a monocotyledonous botanical family belonging to the order *Zingiberales*, comprising 29–31 genera, whose leaves, stems, fruits and rhizomes are used for a wide range of purposes by rural communities in Central Africa. Research on the family *Marantaceae* is extensive. The present bibliographic synthesis summarizes all available information relating to geographical distribution, botanical and economic characteristics, as well as ethnobotanical aspects. This review has highlighted certain gaps concerning the ecology and reproductive modes of the harvested species, despite their importance to local communities. Furthermore, uncertainties about quantities of *Marantaceae* leaves harvested, actual pressures on these resources and their potential for in situ regeneration necessitate investigation to secure sustainable management.

Keywords: *Marantaceae, botany, Ecology, Phenology, Ethnobotany.*

Introduction

The forests of the Congo Basin cover more than 180 million hectares and constitute the second largest continuous tropical forest block after the Amazon [1]. They represent invaluable ecosystems in terms of biodiversity and play a crucial role by providing a wide range of ecosystem goods and services (provisioning, regulating and cultural services) [2]. These forests also provide numerous Non-Timber Forest Products (NTFPs), i.e. fruits and berries, nuts, young leaves, herbaceous plants, gums and saps, invertebrates (insects, snails) vertebrates (fish, birds, mammals, all, biological products derived from forests other than timber [3]. They include resources such as fruits, nuts, mushrooms, medicinal plants, resins, leaves, and other plant products. Furthermore, NTFPs contribute to the local economy and to the livelihoods of both rural and urban communities [4].

Among this wide range of NTFPs are the Marantaceae, which are regularly harvested in Central Africa for numerous purposes, including cassava wrapping, construction, traditional medicine, the provision of raw materials for basketry, food, and wildlife nesting [5-7]. Indeed, these are typical plants of equatorial forests [8]; the mature leaves are not edible but play an essential socio-economic role by ensuring both food security and improving the incomes of households harvesting them [9–12]. Consequently, knowledge and valorization of Marantaceae leaves are important in the sustainable management of forests in the countries of the Congo Basin [13] This article aims to provide a bibliographic synthesis of current knowledge on Marantaceae, highlighting all aspects that warrant further scientific investigation for the sustainable management of this resource for its main users. Specifically, geographical distribution, botanical, ecological and phenological characteristics, as well as ethnobotanical aspects, will be addressed. Finally, several research lines are identified with a view to improving the valorization of Marantaceae.

The literature review was conducted using search engines (Scopus and Google Scholar), complemented by various sources (theses, reports, etc.). Searches combining taxonomic and thematic terms, the Marantaceae value chain, and Non-Timber Forest Products were used, taking taxonomic synonyms into account. The inclusion criteria covered both empirical studies and review papers on Marantaceae in Central Africa, published between 1960 and 2025, in either French or English. Studies lacking a descriptive methodology were excluded. Particular attention was paid to articles dealing with Marantaceae in Central Africa.

Current State of Knowledge on Marantaceae

Taxonomy and geographical distribution

Marantaceae are monocotyledonous angiosperms belonging to the order *Zingiberales* and are considered to be the sister family of the *Cannaceae* [14]. Currently, eight families are recognized within the order *Zingiberales*, namely: the sister families *Zingiberaceae* and *Costaceae*; the sister families *Strelitziaceae* and *Lowiaceae*; the sister families *Cannaceae* and *Marantaceae*; and finally the *Heliconiaceae* and *Musaceae* [15]. The second most important family after the *Zingiberaceae*, it comprises 500–570 species distributed among 29–31 genera [16–19] (Table 1), as shown in Table 1.

Table 1. Classification of the Marantaceae family according to Prince and Kress [19]

Class Name	Include Genus	Geographical Distribution
CALATHEA Class	*Calathea p.p.*	America
	Haumania	Africa
	Monotagma	America
	Pleiostachya	America
DONAX Class	*Cominsia*	Asia
	Donax	Asia
	Phrynium	Asia
	Phacelophrynium	Asia
	Schumannianthus dichotomus	Asia
	Thalia	America
MARANTA Class	*Ctenanthe*	America
	Halopegia	Africa, Asia
	Hylaeanthe	America
	Koernickanthe	America
	Maranta	America
	Myrosma	America
	Saranthe	America
	Schumannianthus virgatus	Asia
	Stromanthe	America
STACHYPHRYNIUM Class	*Afrocalathea*	Africa
	Ataenidia	Africa
	Marantochloa	Africa
	Stachyphrynium	Asia
SARCOPHRYNIUM Class	*Hypselodelphys*	Africa
	Megaphrynium	Africa
	Sarcophrynium	Africa
	Thaumatococcus	Africa
	Trachyphrynium	Africa
Uncertain Affinity	*Monophrynium*	Asia
	Monophyllanthe	Asia
	Sanblasia	America

Essentially pantropical, this botanical family is distributed in warm temperate or subtropical regions and is found almost exclusively in tropical rainforests, humid gallery forests, dry forests, forest edges, clearings, cultivated fields, savannas, and sometimes in very high abundance in wetlands [17,20].

Furthermore, out of approximately 31 genera and 550 species, the Americas and Asia harbour about 14 and 8 genera, respectively, whereas the African flora, although rich in genera (10–12), remains relatively poor in species [19,21] (Fig. 1).

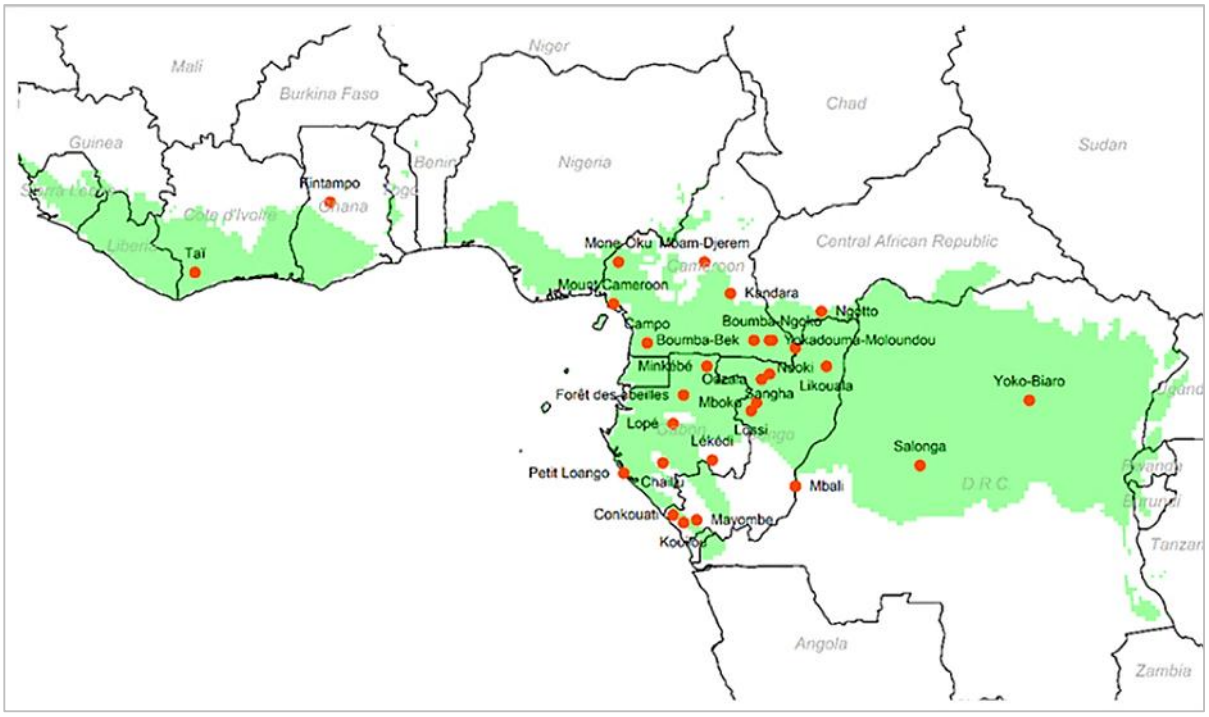


Figure 1. Geographic distribution of Marantaceae in the tropical rainforests of Central and West Africa (red dots indicate recorded occurrences; green shading represents the tropical rainforest biome) [22]

Botanical description

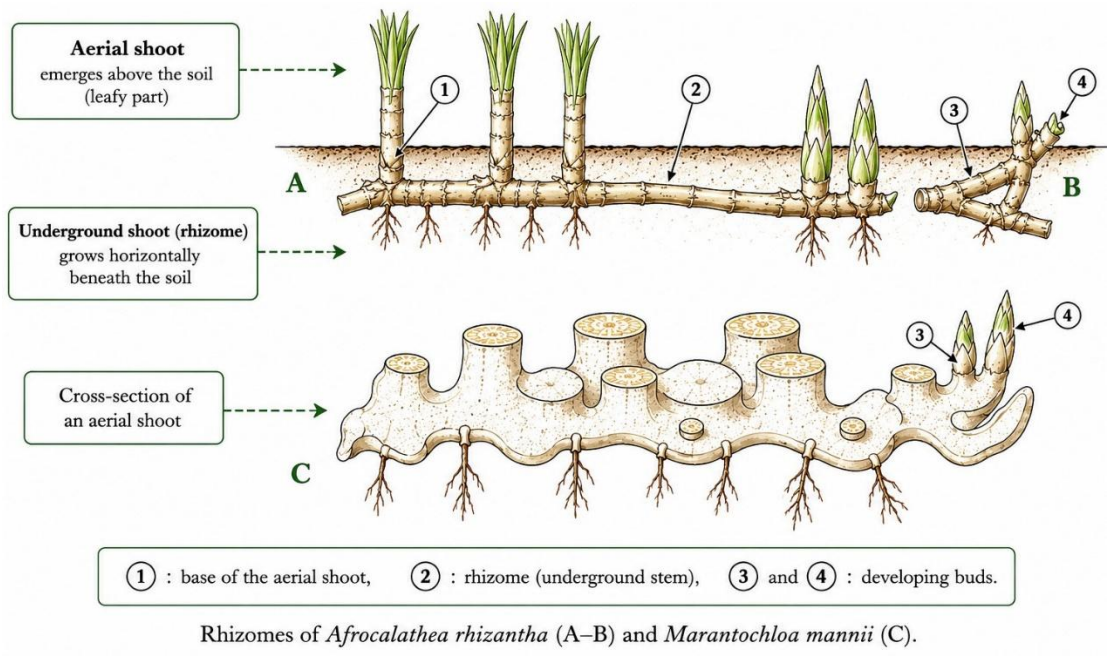
The morphological characteristics of the family *Marantaceae* are mainly based on the description of the vegetative and reproductive structures. The *Marantaceae* of tropical Africa, and of Gabon in particular, have been described respectively by Koechlin and Aubréville [23], Letouzey [8], and Dhetchuvi Matchu-Mandje [17] .

Vegetative structure

Rhizome

Terrestrial herbs, glabrous or bearing variable indumentum, *Marantaceae* are perennial owing to their articulated underground rhizome (Fig. 2), which exhibits sympodial branching (apical degeneration of a bud resulting in zigzag growth). The rhizome, which varies in shape, may be swollen or fleshy (although not in

African species) and bears adventitious roots. Generally short (pachymorphous), it produces both subterranean and aerial shoots, each arising from the preceding shoot. At their bases, the aerial shoots form a bud destined to produce a new plant [17].



Rhizomes of *Afrocalathea rhizantha* (A–B) and *Marantochloa mannii* (C).

Figure 2. Architecture of *Marantaceae rhizomes* [17]

Stem

Certain similarities make it possible to group species according to stem habit. The aerial shoots, which are variable in form, consist of stems (Fig. 3) that may be simple or branched, sometimes highly reduced or even absent. These stems may be greatly elongated, lianescent, provided at the base with aphyllous sheaths (bearing highly reduced leaves), and bear one or several alternate distichous leaves (arranged in parallel on the same plane) or occur in tufts [17].

Four main architectural types were defined by Letouzey [8]:

• The leaves of the plant are clustered in a tuft around the base of the stem: *Halopegia*, *Megaphrynium* and *Sarcophrynium*;

• The stem is lianescent, branched and leafy: *Haumania*;

• The stem is branched and bears oblique leafy branches (bamboo-like appearance): *Hypselodelphys* and *Trachyphrynium*;

• The stem is erect, branched and leafy: most species of *Marantochloa*.

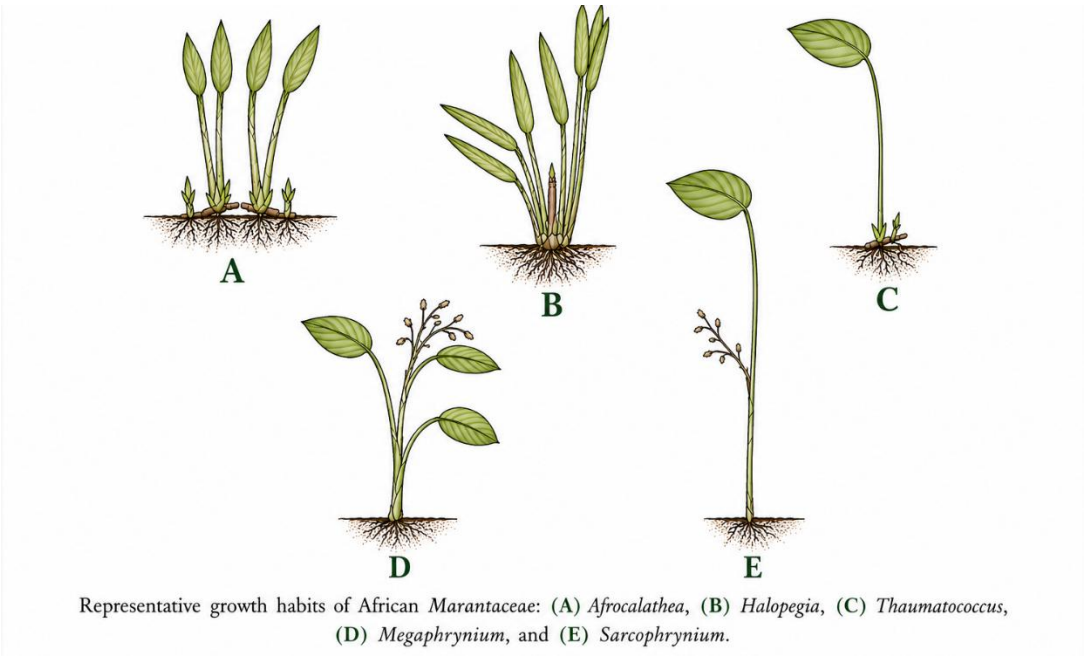


Figure 3. *Representative growth habits of African Marantaceae [17]*

Leaves

As shown in Figue 4, The leaves, with an open sheath, surround the stem and possess a cylindrical petiole whose apex is modified into a specialized structure known as a "callus". The entire lamina, ovate or elliptical in shape, is sometimes large and exhibits two asymmetrical halves relative to the midrib, with one margin convex and the other less curved or straight. The prominent midrib on the lower surface extends into oblique to arcuate parallel lateral venation, of variable density, reaching the margins of the lamina [8].

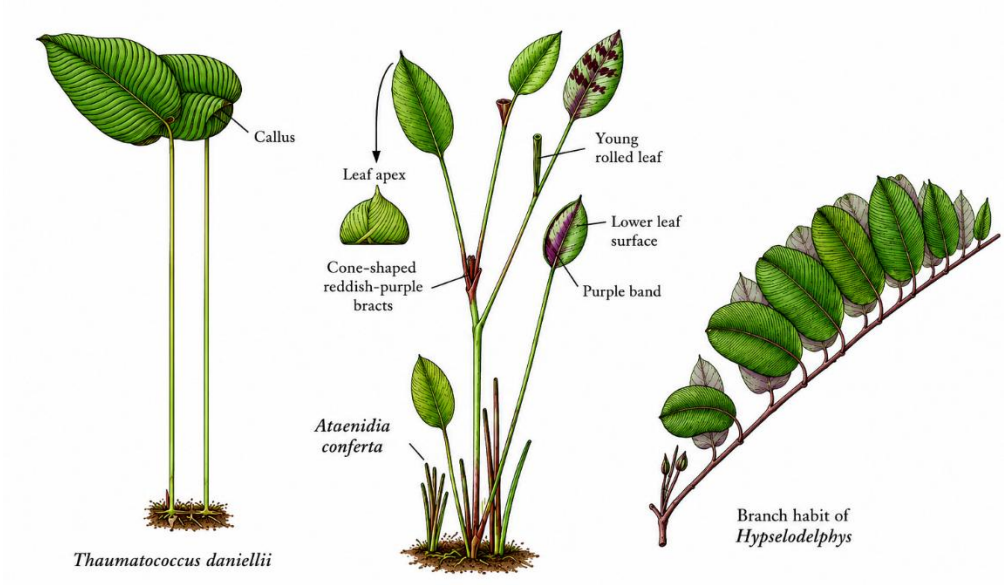


Figure 4. Representative leaf morphology of African Marantaceae [8]

a. Leaf systems : antitropy and homotropy

Two leaf systems are observed in *Marantaceae*, namely those in which two successive leaves of a species arranged opposite each other either overlap distinctly or do not. In the first case, the arrangement is referred to as homotropy (homotropic leaves), whereas in the second case it is referred to as antitropy (antitropic leaves) [17].

b. Shape of the lamina

The lamina generally exhibits one side that is more or less parallel to the midrib, but the other side is more curved. Consequently, the acumen is not located exactly along the extension axis of the midrib. This is the case in species of the genus *Marantochloa* and in *Ataenidia conferta*. In species belonging to the genera *Hypselodelphys* and *Trachyphrynium*, this organization is less pronounced. In other genera such as *Megaphrynium*, *Sarcophrynium*, *Thaumatococcus* and *Thalia*, both sides of the lamina are almost rounded [17].

Reproductive structure

Inflorescence

The inflorescences (Fig. 5) are terminal or lateral, basal or radical (arising from the root), arranged in racemes or in clusters of biflorous cymes. The peduncle is simple or branched from the base, and the articulated rachis bears at each node a spatheole subtending one or several biflorous cymes, each provided or not with a bract. The cyme, consisting of a common axis, bears at its apex two generally unequal pedicels, each terminating in a flower, and the pedicels may or may not bear one or two fleshy bracteoles [8].

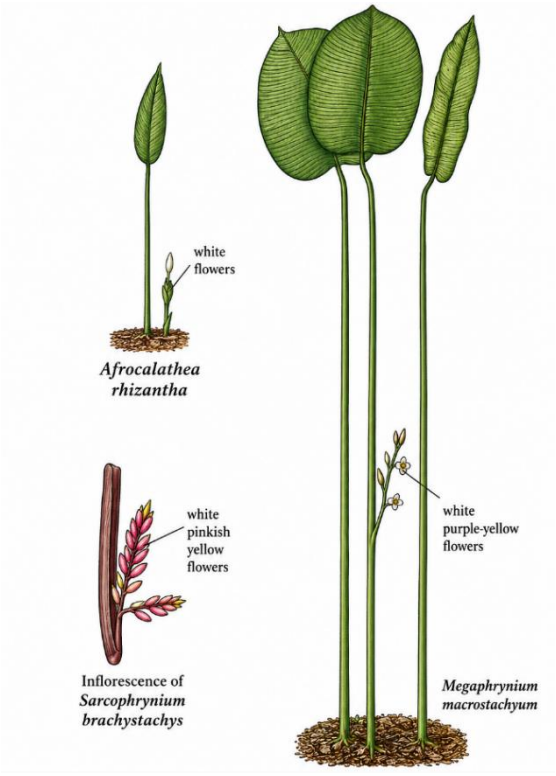


Figure 5. Representative inflorescences of African Marantaceae [8]

Flower and nectaries

The flowers, as shown in Fig. 6, are trimerous, zygomorphic and hermaphroditic. The free sepals are generally equal. The corolla, fused into a tube at the base, is divided into three free lobes. Theoretically, the flower possesses six stamens arranged in two whorls, with at least one stamen always absent from the outer whorl [24]. The androecium forms a complex structure, tubular at the base and largely petaloid. The outer whorl, composed of 0, 1 or 2 petaloid staminodes, is broad or acute, whereas the inner whorl comprises three structures, two of which are entirely staminodial: one hood-shaped, sometimes appendaged, and the other callose and thickened. The third is half-staminodial and half-fertile, bearing an anther. The inferior ovary is tricarpellate and trilocular, with one basal ovule per locule. The thick style is curved, initially enclosed within the hooded staminode and subsequently becoming free [8].

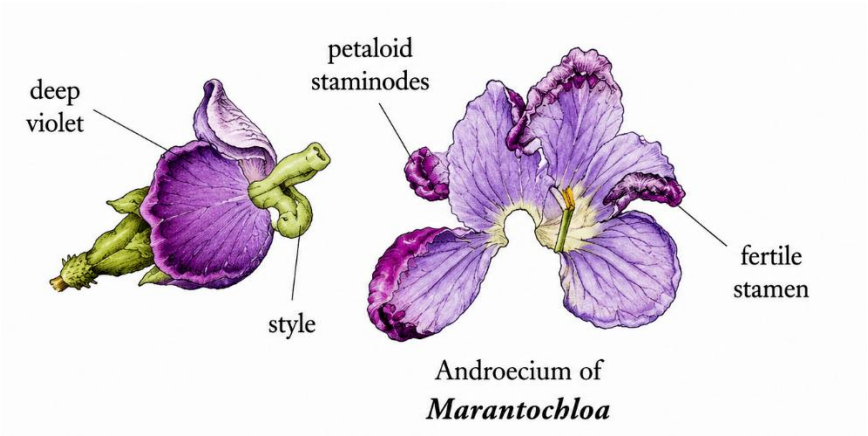


Figure 6. Flower morphology of *Marantochloa purpurea* [8]

Nectaries consist of glandular tissue secreting a sugar-containing fluid. Both floral and extrafloral nectaries occur. The latter are located on stems, petioles, stipules, leaf margins, etc., whereas the others are floral nectaries [17]. According to the same author, floral nectaries located on the bracts are found in the species *Hypselodelphys hirsuta*, *H. poggeana*, *H. violacea*, *Sarcophrynium brachystachium*, *S. pionogonium*, *S. schweinfurthianum*, *Megaphrynium macrostachyum* and *Thaumatococcus daniellii*. Extranectaries, on the other hand, are found in *Haumania liebrechtsiana* and *H. danckelmanniana* [17].

Fruit and seeds

The fruits illustrated in Figure 7 are either capsular or berry-like, and may be dry, dehiscent or indehiscent. The seeds are often either arillate or non-arillate, with either coriaceous or non-coriaceous seed coats, and possess either rudimentary or well-developed embryos, which may be straight or curved, with a variable perispermatic canal [8].

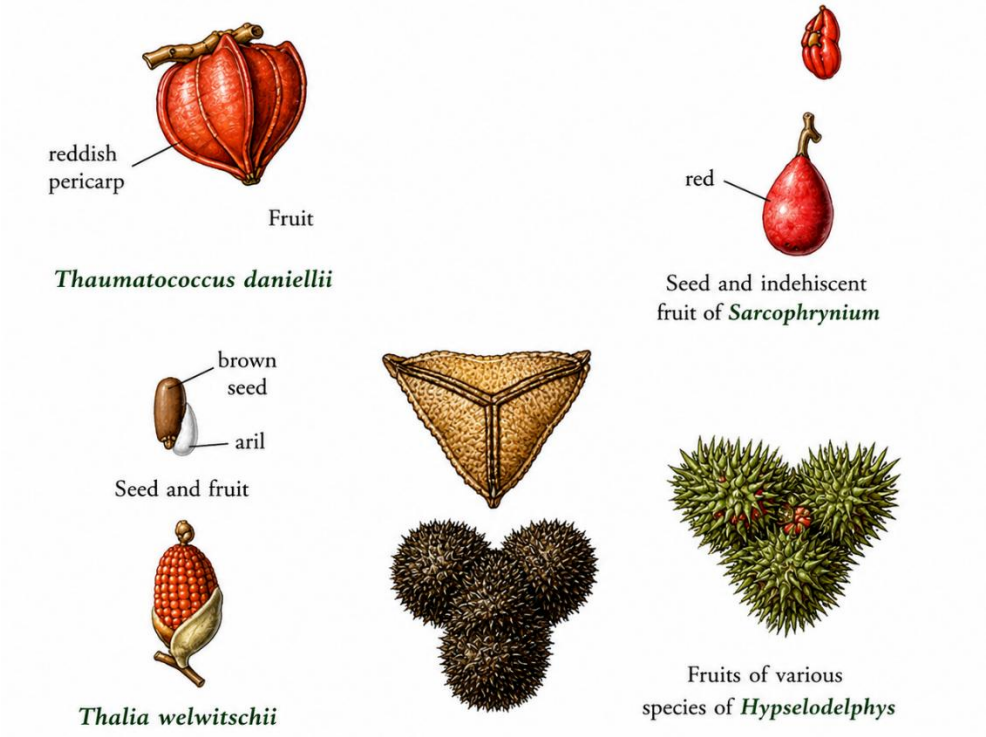


Figure 7. Representative fruits and seeds of African Marantaceae [8]

An aril is present in all African *Marantaceae* except in *Haumania*, *Hypselodelphys* and *Sarcophrynium*. Its form differs among genera. Indeed, the aril is bifid in *Ataenidia*, collar-shaped in *Halopegia*, convoluted in *Thalia*, laciniate in *Trachyphrynium* and *Megaphrynium*, and lamellar or entire in *Marantochloa* [17]. According to the same author, the genera possessing smooth, more or less soft seed coats are *Ataenidia*, *Halopegia*, *Haumania*, *Hypselodelphys*, *Marantochloa*, *Thalia* and *Trachyphrynium*, whereas those with hard seed coats and irregular surfaces are *Megaphrynium*, *Sarcophrynium* and *Thaumatococcus* [17].

Some Genera of the Family Marantaceae

Ataenidia Benth [17]

Herbs with a short, highly branched sympodial rhizome, producing erect, branched aerial shoots arranged in dense tufts. Leaves homotropic, with petioles sometimes very elongated, possessing a swollen callus; the transition from the petiole to the callus marked by an oblique ridge, with the apex on the ventral side and the base on the dorsal side; the transition from the callus to the midrib V-shaped on the upper surface. Lamina elliptical, markedly asymmetrical, with the acumen laterally displaced relative to the axis of the midrib. Dense axillary inflorescences, racemose, with few and very short internodes; spatheoles narrowly imbricate; bracts present; common axes of the cymes very short; floral pedicels also very short and subequal; bracteoles absent; two external

petaloid staminodes; internal hood-shaped staminode without appendages; ovary trilocular with one ovule per locule. Indehiscent fruits bearing seeds with a bifid basal aril.

This genus comprises two species, namely: *Ataenidia gagnepainii* Benth. and *Ataenidia conferta* (Benth.) Milne-Redh.

Halopegia azurea K. Schum [17]

Herb with a rhizome provided with numerous roots. Aerial shoots 0.7–2 m high, consisting of a stem 10–20 cm long, pubescent, with caducous hairs, swollen at the base, bearing a tuft of 2 to 10 leaves sheathing at the base and a final leaf at the apex. Leaves with a sheath approximately 50 cm long, with glabrous membranous margins, densely hairy externally, especially in the median and marginal zones, with tuberculate hairs; petiole 20–80 cm long, with caducous hairs; callus 3–6 cm long, with persistent hairs on the inner surface of the apex; lamina asymmetrical, rectangular to oblong, with the right side almost parallel to the midrib, cuneate at the base, long-acuminate at the apex, acumen approximately 5 cm long, situated along the extension of the midrib, 20–60 cm long and 8–13 cm wide, hairy on the upper surface along the midrib. Racemose inflorescence located inside or outside the sheath tuft, initially enclosed within the leaf sheath and becoming visible at maturity, approximately 60 cm long, repeatedly branched from the base; peduncle approximately 20 cm long, pubescent; rachis pubescent; lower pedicels approximately 4 cm long, the upper ones progressively shorter; spathes approximately 20 cm long, membranous at the margins, pubescent in the median zone, with woolly hairs; spatheoles approximately 6 cm long, with membranous margins, white; white bracts 4 cm long, with two hairy keels. Flowers with unequal sepals, small, white; petals white; three external petaloid staminodes, violet-blue, one of which is keeled and hardened; two internal staminodes with yellow apices, one larger and petaloid, with one yellowish theca; style white; ovary pubescent. Unilocular ellipsoid fruits, firm in texture, approximately 1.2 cm long and 0.5 cm wide, glabrous, smooth, white to brown, surmounted by the persistent calyx. Single seed, ellipsoid, with a collar-shaped aril at the base, with a thin seed coat, smooth externally; perispermatic canal straight; embryo straight, parallel to the perispermatic canal, approximately 1 cm long.

Haumania Leonard [17]

Rhizomatous herbs with climbing aerial shoots, internodes glabrous, hairy or spiny; branches provided at their base with 2 to 3 small aphyllous sheaths, 5 to 8 cm long, puberulent, with appressed hairs and ciliate margins. Leaves antitropic, more or less clustered, with elongated, imbricate sheaths; transition from petiole to callus continuous, transition from callus to midrib

marked by a prominent beak forming a V on the upper surface, but continuous on the lower surface; leaf sheath provided with a tuft of hairs on the inner surface of the apex; petiole with thickened hairs on the inner surface. Lamina ovate-oblong, broadly rounded at the base, more or less long-acuminate, symmetrical to slightly asymmetrical, hairy along the midrib on the lower surface; extrafloral nectaries visible at the junction between petiole and sheath and also in the median zone at the base of the sheath. Terminal inflorescences in clusters of cymes, supported at the base by long aphyllous sheaths; rachis zigzag-shaped, bearing at each node a large, more or less persistent spatheole enclosing a sickle-shaped group of 3 to 6 biflorous cymes, each subtended by a bract; common axes of cymes short; floral pedicels lacking bracteoles; perianth petaloid; corolla tubular at the base; staminodes petaloid; ovary trilocular with one ovule per locule, densely hairy. Capsules indehiscent and tuberculate. Seeds subspherical, with one flattened face, lacking an aril, with albumen differentiated into two zones, one external, thin and hardened, the other internal, broader and soft, surrounding the embryo; perispermatic canal U- or H-shaped in median transverse section. This genus comprises three species:

- *Haumania danckelmanniana* (J. Br. & K. Schum.) Milne-Redh.;
- *Haumania liebrechtsiana* (De Wild. & Th. Dur.) J. Leonard;
- *Haumania leonardiana* Evrard & Bamps.

Megaphrynium Milne-Redh [17]

Herbs with a linear and robust rhizome producing erect aerial shoots consisting of simple stems terminating in a leaf and an inflorescence; stem base surrounded by aphyllous sheaths or occasionally by complete leaves, with very long petioles. Lamina broadly elliptical to broadly ovate, rounded at the base and then attenuate just before insertion, acuminate at the apex, generally large; transition from petiole to callus continuous, and from callus to midrib continuous on the lower surface but marked by a V-shaped beak on the upper surface. Terminal paniculate inflorescence, with racemes composed of clusters of cymes, sometimes with numerous segments; spatheoles rapidly caducous, subtending a single biflorous cyme; bicarinate bracts, rapidly caducous; common floral axis of variable length, bearing a single fleshy bracteole at the apex between the pedicels; pedicels subequal. Flowers with free sepals, ± adnate to the corolla; petals fused at the base; external staminodes narrowly linear or subulate, more often unequally trilobed; one of the internal staminodes appendaged; ovary trilocular with one ovule per locule. Capsules globose, slightly trilobed, with visible sutures, dehiscent, with a fleshy pericarp when fresh, glabrous. Seeds with a laciniate aril appressed against the seed coat and surrounded by abundant

clear to white mucilage, with a thick and hard seed coat of irregular surface; perispermatic canal flattened, narrow at the base and then broad.

The genus includes four species from the Guineo-Congolian region of Africa, namely: *Megaphrynium gabonense* Koechlin, *Megaphrynium trichogynum* Koechlin, *Megaphrynium macrostachyum* (Benth.) Milne-Redh., and *Megaphrynium velutinum* (Baker) J. Koechlin.

Sarcophrynium [17]

Herbs with a short rhizome, repeatedly branched, producing aerial shoots in tufts composed of a number of distichous leaves, with sheaths narrowly imbricated around a central stem bearing a leaf at its apex. Lamina asymmetrical, pleated along the lateral veins, elliptical, often slightly cordate at the base; transition from callus to petiole without articulation marked by a groove, transition to the lamina continuous on the lower surface but marked on the upper surface by a V-shaped notch. Terminal inflorescences spike-like or paniculate, branched from the base; rachis with zigzag segments, each node bearing a persistent spatheole subtending 4 to 10 biflorous cymes, each provided with its bract; common floral axes very elongated, longer than the spatheoles; pedicels markedly unequal, bearing one fleshy bracteole at their base and another at the apex of the longer pedicel. Flowers with free, obovate sepals; ovary trilocular with one ovule per locule, glabrous; two external petaloid staminodes, obovate. Berries indehiscent, with poorly marked sutures. Seeds crescent-shaped, with a roughly rhomboid or hexagonal cross-section, lacking an aril but embedded in colourless to white mucilage.

The genus comprises four species and three varieties, all restricted to the Guineo-Congolian region of Africa:

- *Sarcophrynium villosum* (Benth.) K. Schum.
- *Sarcophrynium brachystachyum* (Benth.) K. Schum.
    - *Sarcophrynium brachystachyum* var. *brachystachyum*
    - *Sarcophrynium brachystachyum* var. *puberulifolium* Koechlin
- *Sarcophrynium prionogonium* (K. Schum.) K. Schum.
    - *Sarcophrynium prionogonium* var. *prionogonium*
    - *Sarcophrynium prionogonium* var. *puberulifolium* Schnell
- *Sarcophrynium schweinfurthianum* (O. Kuntze) Milne-Redh.
    - *Sarcophrynium schweinfurthianum* var. *schweinfurthianum*
    - *Sarcophrynium schweinfurthianum* var. *puberulifolium* Koechlin

Ecology and Regeneration Dynamics of Marantaceae

African *Marantaceae* occur in forest formations that are more or less humid. Several habitat types have been recorded, including cultivated fields, clearings, gallery forests, heterogeneous forests, flooded and swamp forests, ombrophilous forests, disturbed forests, riparian and riverine forests, dry forests, secondary forests, semi-deciduous forests, forest edges, marshes and savannahs [17].

The distribution and abundance of plant species, as well as the grouping of vegetation types, are determined by certain key ecological factors such as soil type, nutrient availability and the amount of precipitation [25]. These plants, abundant in former clearings [8] and on abandoned cultivated lands in logged forests [26] with open canopies [27], generally emerge in the presence of light and are considered heliophilous, such as *Halopegia azurea*, *Marantochloa congensis* var. *congensis*, *Megaphrynium macrostachyum* and *Thalia geniculata*. Some taxa are sciaphilous, including *Haumania danckelmanniana* and *Haumania liebrechtsiana* (at a young age), *Afrocalathea rhizantha*, *Sarcophrynium schweinfurthianum* var. *schweinfurthianum*, *Sarcophrynium prionogonium* var. *prionogonium*, *Marantochloa conferta* and *Marantochloa congensis* var. *nitida* [17,28].

Most taxa occur in regions receiving more than 2,000 mm of rainfall annually. Regarding altitudinal distribution, most taxa are found between 0 and 1,000 m above sea level [17].

Marantaceae forests result from the progressive colonization of savannahs by forests [29,30], and canopy opening is important depending on the extent of the herbaceous layer [31]. The work of Gillet [28] proposes several hypotheses related to the expansion of the *Marantaceae* front, including the action of large mammals, gap dynamics (canopy opening following the fall of a large tree), low tree stand density and the near absence of woody regeneration, as well as spontaneous or repeated anthropogenic fires, which also favour the survival of these giant herbs through their underground rhizomes, usually little affected by fire. Furthermore, *Marantaceae* formations, owing to their large leaf area, would be favoured on yellow soils where water availability is continuous and non-limiting [28].

In Gabon, particularly in Moyabi, there is a strong proliferation of *Marantaceae* in landscapes surrounding dwellings, such that their collection by rural populations does not require travelling long distances. Harvesting of this plant, within the limits of the average exploited leaf area in this locality, amounts to 1,379 cm² [20].

Table 3 shows the morphological types of some African *Marantaceae* genera.

Table 3. Morphological types of some African *Marantaceae* genera [17,32].

Genera	Morphological Types	Sites	Habitats
Afrocalathea	Perennial herbaceous plant	Ma, MC	Ombrophilous forest
Ataenidia	Perennial herbaceous plant	Ma	Forest, terra firme forest, gallery forest, swamp forest, ombrophilous forest
Halopegia	Perennial herbaceous plant	Ma, MC	Swamp forest, swamp clearing, ombrophilous forest
Haumania	Liana	Ma, MC	Dense flooded forest, ombrophilous forest, forest edge
Hypselodelphys	Liana	Ma, MC, Si, Lo	Forest roadside, treefall gaps, secondary forest, gallery forest, forest edge
Marantochloa	Perennial herbaceous plant	Ma, MC, Si, MZ	Forest, ombrophilous forest, secondary forest, forest edge, terra firme forest, fallow land
Megaphrynium	Perennial herbaceous plant	Ma, MC, Si	Forest, secondary forest, gallery forest, swampy valley understorey, clearing
Sarcophrynium	Perennial herbaceous plant	Ma, MC	Open flooded forest, gallery forest, secondary forest, forest clearing, swamp
Thalia	Perennial herbaceous plant	MZ	Gallery forest, swamp forest, swamp in savanna
Thaumatococcus	Perennial herbaceous plant	Di, MC	Stream bank, secondary forest, ombrophilous forest, fallow land
Trachyphrynium	Liana	Ma, Lo	Forest clearing, gallery forest, secondary forest, forest edge and swamp

Di: Dibouka; **Ma**: Makokou; **MC**: Monts de Cristal; **Lo**: Lopé; **Si**: Sibang; **MZ**: German herbarium.

Phenology and Modes of Propagation of Marantaceae

In Marantaceae, flowering is reported to begin in October for 17 out of 42 taxa. But, no study has documented the onset of fruiting in all taxa, except for those observed in their natural environment, where anthesis occurs progressively and flowers remain open for two days. Young fruits can be observed after one week [17]. Thus, taxa such as *Haumania leonardiana*, *Hypselodelphys poggeana*, *H. scandens*, *Marantochloa filipes*, *Thalia geniculata* and *Trachyphrynium braunianum* are reported to produce flowers almost throughout the year, whereas with others this period varies from 3 to 6 months (*Ataenidia conferta*, *Halopegia azurea*, *Haumania liebrechtsiana*, *Hypselodelphys violacea*, etc.). Other taxa, such as *Marantochloa cordifolia*, *Sarcophrynium brachystachyum* var. *brachystachyum* and *Sarcophrynium prionogonium* var. *prionogonium*, are believed to have a short reproductive period and may even reproduce twice a year. Flowering beginning in October coincides with the peak rainfall period in the Guineo-Congolian region [17]. A recent study conducted in Cameroon on the phenology of *Megaphrynium macrostachyum*

showed the existence of two phenological phases: the flowering phase, which extends from May to June, and the fruiting phase, which lasts from June to August. The period from flowering to fruiting varies between 64 and 85 days, corresponding to approximately 2 to 3 months [33].

Single-visit pollination is a characteristic mechanism of *Marantaceae*, including protandry, secondary pollen presentation and an irreversible movement of the style [34–37]. The flowers are asymmetrical and attract their pollinators through conspicuous staminodes and nectar [38,39]. Moreover, as each flower has only one opportunity to be pollinated and to disperse its own pollen, it remains open for only a single day, since the explosive pollination mechanism cannot be reset [36,40].

Numerous authors [32,34,36,37,41-45] have recorded species of small, medium-sized and large bees belonging respectively to the families Halictidae (*Thrinchostoma* sp.) and Apidae (*Allodapula ornaticeps*), Apidae (Amegilla vivida) and Anthophoridae (*Xylocopa nigrita*, *Xylocopa varipes* and *Megachile* sp.), as well as birds belonging to the families Nectariniidae (*Cyanomitra olivaceus*) and Trochilidae (hummingbirds), as pollinators of Marantaceae in the New World, Asia and Central Africa, particularly in Gabon (Table 4). Foucault *et al.* [46] also reported pollination by zoogamy.

Above the herbaceous layer that inhibits woody regeneration, some lianescent and climbing *Marantaceae* encircle tree trunks or cover the crowns of the few shrubs present, thereby hindering their development and even their reproduction [29,47]. They may thus monopolize the acquired space for long periods and expand through adjacent gaps [48,49]. These large terrestrial and occasionally aquatic herbs develop very slowly from seeds because of competition; consequently, their preferred mode of propagation is vegetative, particularly through the spread of perennial underground stems or rhizomes [28,49,50].

Another form of clonality commonly observed in certain taxa is vivipary, particularly in *Costus lucanusianus* and *Ataenidia conferta*. The extremities of stems bearing old inflorescences produce a young plant; the stems bend through senescence and gravity, allowing the clone to take root [50,51]. Lianescent *Marantaceae* of the genus *Haumania* propagate by producing very long articulated stems, reaching up to 5 m in length and covered with aphyllous sheaths. These flagella branch when they come into contact with a support. The base of each node bends to attach itself to the support, while the internode swells and hardens on the opposite side in order to maintain the acquired position [52].

Table 4. Pollinators of some African Marantaceae species according to Ley and Claßen-Bockhoff [32].

	Pollinating bees			**Birds**
Species	**Small**	**Medium**	**Large**	
Ataenidia conforta	-	-	*Xylocopa sp*	*Cyanomitra olivaceus*
Afrocalathea rhizantha	-	-	-	*Cyanomitra olivaceus*
Halopeia azurea	*Thrinchostoma bicometes* -		-	-
Haumania danckelmanniana	-	-	*Xylocopa nigrita; X.varipes;Megachile* sp.*2*	
Hypselodelphys sp.	-	*Amegilla vivida*	-	-
Marantochloa cordifolia	*Thrinchostoma* sp	*Amegilla sp.*	-	-
Marantochloa incertifolia	*Thrinchostoma* sp	-	-	-
Marantochloa monophylla	*Allodapula ornaticeps*	-	-	-
Marantochloa congensis	*Thrinchostoma* sp	-	-	-
Marantochloa filipes	*Thrinchostoma* sp	-	-	-
Marantochloa sp.	-			*Cyanomitra olivaceus*
Megaphrynium gabonense	-	*Amegilla vivida*	*Xylocopa varipes;Megachile sp .*	-
Megaphrynium macrostachyum	-	*Amegilla vivida*	-	-
Megaphrynium trichogynum	-	-	-	*Cyanomitra olivaceus*
Sarcophrynium brachystachyum	*Thrinchostoma* spp	-	-	-
Sarcophrynium prionogonium	*Thrinchostoma* spp	-	-	-

Importance of Marantaceae

Food Importance for Wildlife

The investigation conducted by White *et al.* [6] on the herbaceous vegetation of the different forest types in the Lopé Reserve (Gabon) revealed the influence of habitat on resource availability and the role of *Marantaceae* in wildlife feeding. Indeed, this study showed that plants such as *Halopegia azurea* K. Schum., *Haumania liebrechtsiana* (De Wild. & T. Durand) J. Léonard, *Hypselodelphys violacea* (Ridl.) Milne-Redh., and *Marantochloa cordifolia* (K. Schum.) Koechlin are consumed by gorillas (*Gorilla gorilla* Geoffroy), chimpanzees (*Pan troglodytes* (Blumenbach) L.), mandrills (*Mandrillus sphinx* L.), and elephants (*Loxodonta africana* Blumenbach) [6]. In

addition to serving as a food resource, *Marantaceae* are also used by great apes for nest construction [7].

Furthermore, several studies have highlighted the importance of habitat types and the impact of human activities on the distribution and population densities of western lowland gorillas in Cameroon [53]. Habitat disturbance and modification constitute major threats to animal populations in tropical forests [54]. In Lobéké National Park, Cameroon, *Marantaceae* forests are preferentially used by gorillas for nest construction. Indeed, 49% of gorilla nests are concentrated in these areas [53], and gorillas also use *Marantaceae* as a food resource.

Pharmacological Importance

This family of multipurpose plants provides considerable pharmacological benefits [13]. Indeed, a phytochemical study revealed the antibacterial properties of *Marantochloa cuspidata* (Roscoe) Milne-Redh. [55]. In another phytochemical study on the fruits of *Megaphrynium macrostachyum* (Benth.) Milne-Redh., Ondo *et al.* [56] demonstrated the presence of phenolic compounds capable of preventing the development of cardiovascular diseases and cancer.

Similarly, Njintang *et al.* [57] and Joly *et al.* [58] reported that the crushed stem of *Calathea warscewiczii* (L. Mathieu ex Planch.) Planch. & Linden, infused in lukewarm water, is consumed to treat rubella (a contagious viral infection) among the Guaymi Indians of western Panama. In India, the daily consumption of milk containing powdered rhizome of *Maranta arundinacea* L. is reported to treat asthma [59]. Among the Passa Pygmies in the Central African Republic, the fruits of *Trachyphrynium braunianum* (K. Schum.) Baker, consumed raw, are believed to have medicinal properties for the prevention of miscarriages [60].

According to Hattori [61], among Baka women in Cameroon, the root of *Haumania denckelmanniana* (J. Braun & K. Schum.) M.-Redh. is used medicinally for wound treatment, and the root of *Hypselodelphys scandens* Louis & Mullend. is used to relieve headaches. In addition, the flowers of *Ataenidia conferta* (Benth.) M.-Redh. are used as a protective charm during honey harvesting, and the root of *Trachyphrynium braunianum* (K. Schum.) Baker is used as a remedy for illnesses caused by *behe*, an unidentified fish species.

Socio-cultural Importance

In general, the broad leaves of *Marantaceae* are used for wrapping various food products; they may also be used in place of cooking utensils for preparing certain foods, such as meat or fish, by steaming. They are mainly employed for wrapping cassava products [5,9,11,52,62]. In Côte

d'Ivoire, wrapped foods are often associated with traditions of hospitality and conviviality and form part of the social customs of most families [63]. Indeed, offering food wrapped in leaves to an authority figure or a stranger is considered a sign of great respect [64].

As regards the stems, those of *Megaphrynium macrostachyum* and *Trachyphrynium braunianum* are used in basketry for making fish traps, fishing baskets, rat traps, and even the frameworks of huts among Pygmy communities in Gabon, the Democratic Republic of the Congo, and Cameroon [5,52,61,65]. Traditionally, it is Pygmy women who collect the leafy stems of *Marantaceae*. Furthermore, the pulp of the fruit of *M. macrostachyum* is edible [49,66]. Among the Baka Pygmies of Cameroon, the seeds of *Haumania denckelmanniana* (J. Braun & K. Schum.) M.-Redh. and *Trachyphrynium braunianum* (K. Schum.) Baker are roasted and eaten as snacks [61].

According to Terashima and Ichikawa [67], Central African hunter-gatherers use *Marantaceae* plants in many aspects of daily life, from the cradle—by giving birth on the leaves of *Megaphrynium macrostachyum* (Benth.) M.-Redh.—to the grave, by wrapping the bodies of the deceased in the leaves of *Ataenidia conferta* (Benth.) M.-Redh.

Walker and Sillans [68] reported that, among the Mitsogho initiated into the Nyèmbè or Ndjèmbè sect, *Marantaceae* possess mystical attributes and that their association with other plants serves as protection (fetishes) against logging accidents. The leaves of *Thalia welwitschii* Ridl., rolled into cones, are used as stoppers for bottles and gourds among the Mbuti Pygmies in the Democratic Republic of the Congo [65], whereas those of *Sarcophrynium brachystachyum* and *Megaphrynium macrostachyum* are used to wrap cassava sticks and to line the bottoms of cooking pots when preparing food (bananas, yams, taro, meat, and fish) in the forest [68].

The young shoots of *Megaphrynium macrostachyum*, known as "Mikungu" in the Democratic Republic of the Congo, are consumed as vegetables by certain tribal populations and in other African countries [69]. These young shoots, preserved by salting, ensure the year-round availability of this vegetable [70]. In the case of *Maranta arundinacea*, although arrowroot starch is obtained from its rhizomes and used to produce an edible flour in the Caribbean [71], in Gabon it is used solely as starch [68].

Economic Importance

Marantaceae are NTFPs with commercial value and contribute to local economies. Indeed, the genus *Calathea* G. Mey., which is selected and cultivated in Florida for commercial purposes [72], is also found in horticultural stations in Togo [73]. In the Republic of the Congo, the most commercialized species are *Marantochloa congensis*, *Marantochloa purpurea*, *Megaphrynium*

macrostachyum, *Sarcophrynium brachystachyum* and *Thaumatococcus daniellii*, and these are sold in more than 76% of the markets in Kisangani, dominating the various markets with a substantial estimated daily value [10,74,75].

In the same region, Loubelo [9] observed that intensive annual exploitation of this natural resource (*Marantaceae*) by local populations could contribute to its regeneration through the exclusive harvesting of mature leaves for commercial purposes. This resource contributes to food security within the agri-food sector through its use as plant-based packaging [76]. *Marantaceae* are considered to be the second most widely sold NTFP in the Republic of the Congo after *Gnetum* sp. (Gnetaceae), with an estimated annual value of 142,248,000 FCFA for approximately 3,500,000 bundles of leaves displayed in urban markets [9]. According to the same author, bundles of *Marantaceae* leaves purchased in villages at unit prices of 50, 75 or 100 FCFA are resold at retail markets in Brazzaville for 150, 200 or even 250 FCFA, generating a monthly income of 520,000 FCFA per vendor. Nevertheless, a vehicle in good condition may undertake two to three trips per week, transporting between 90,000 and 120,000 kg per month. The sale of these quantities corresponds to a gross net income ranging from 4,000,000 to 7,000,000 FCFA per month at prices of 200 to 250 FCFA per bundle. These prices fluctuate according to market conditions [9]. Consequently, the trade in *Marantaceae* leaves undoubtedly constitutes a significant source of income capable of alleviating the daily economic hardship experienced by Congolese populations [10,75].

In Gabon, *Marantaceae* leaves (*Megaphrynium macrostachyum* and *Sarcophrynium brachystachyum*) are regularly sold in markets located in urban centres. Weekly quantities collected range from 1,000 to 5,000 leaves per village, whereas the quantities sold vary between 2,000 and 4,000 leaves [11]. This demonstrates that the quantities of *Marantaceae* leaves marketed reflect the ever-increasing pressure exerted on this resource by local populations [77].

Conclusion and Perspectives

The current state of knowledge on *Marantaceae* highlights their importance for numerous rural populations in Central Africa. The family appears to be well documented in terms of botanical, anatomical and ethnobotanical descriptions. Indeed, *Marantaceae* comprise numerous genera and species that are commonly harvested and marketed by local communities, thereby providing them with significant employment opportunities and income.

Further investigation is desirable in order to propose sustainable resource management measures. New studies are required to:

✓ Complete ecological data on regularly used species, their modes of regeneration and population dynamics, in order to provide essential information for the development of resource management strategies;

✓ Quantify the levels of *Marantaceae* leaf harvesting by local populations, based, for example, on factors such as harvested species, quantities collected and exploited leaf areas;

✓ Assess the modalities and impacts of *Marantaceae* exploitation as indicators of pressure on resource availability in forests;

✓ Evaluate the domestication potential of the most frequently harvested species with a view to integrating *Marantaceae* into local agroforestry systems;

✓ Estimate the actual or potential contribution of *Marantaceae* to household and local economies through the identification of marketing chains.

The simultaneous consideration of these five research dimensions should provide the basic elements required to envisage the sustainable exploitation of this resource. Consequently, improving the tools used to assess these resources better and gaining greater control over the socio-economic factors leading to their overexploitation is necessary and should be expedited.

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Modelling the Economic Resilience Effects of Climate Adaptation Infrastructure Investments in Senegal: Evidence from a Dynamic Stochastic General Equilibrium (DSGE) Model

Bruno Tiendrébéogo [a], Assana-Richard Ayizou [b], Oumy Ndiaye [c*]

National School of Statistics and Economic Analysis Pierre Ndiaye (ENSAE Dakar), Cheikh Anta Diop University, Dakar, Senegal

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[a] ***ORCID:*** *****-****-****-****; **Email**:bruno20tiendre@gmail.com*

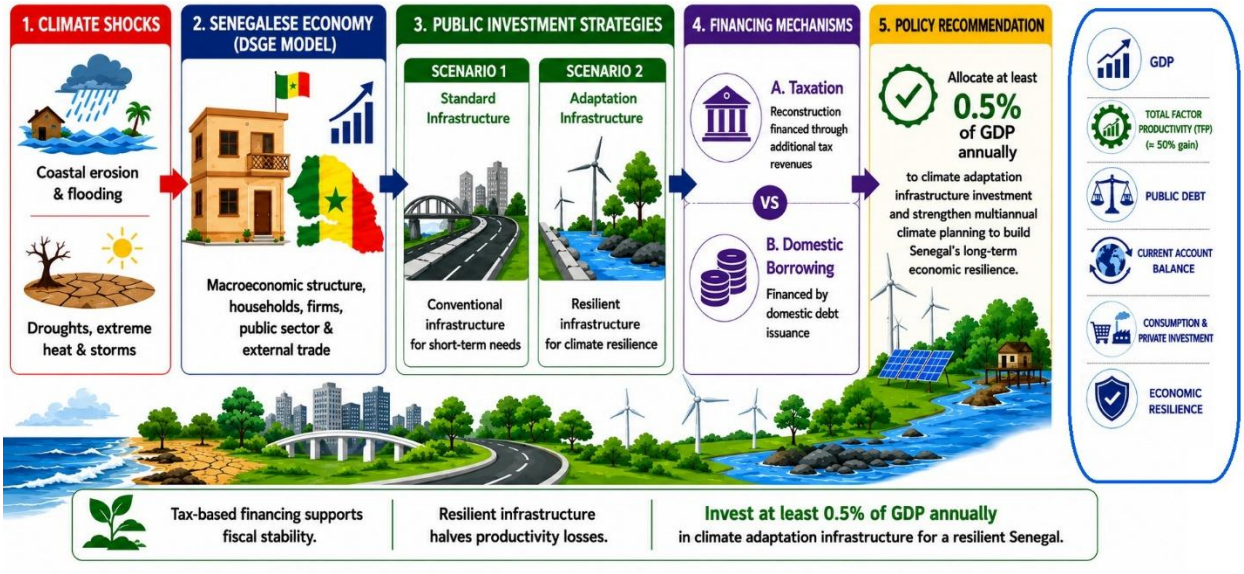
[b] ***ORCID***: *0009-0004-5492-6965; **Email** : assanarichardayizou@gmail.com*

[c] ***ORCID:*** *0009-0009-0507-1370 ;**Email**:oumy3.ndiaye@gmail.com ; oumy3.ndiaye@ucad.edu.sn*

* **Corresponding author:** Oumy Ndiaye; ***Email***: *oumy3.ndiaye@gmail.com; oumy3.ndiaye@ucad.edu.sn*

Graphical abstract

Senegal is a coastal country in sub-Saharan Africa that is increasingly exposed to coastal erosion and seasonal flooding. This study analyses the macroeconomic effects of a major climate shock using a dynamic stochastic general equilibrium (DSGE) model, with particular attention to post-disaster financing mechanisms and public investment choices. The findings show that tax-based reconstruction financing supports fiscal stability more effectively than domestic borrowing, while resilient infrastructure substantially reduces productivity losses and reconstruction costs. These results suggest that allocating at least 0.5% of GDP to climate adaptation investment could strengthen the country's long-term resilience to climate change.


1. CLIMATE SHOCKS
Coastal erosion & flooding
Droughts, extreme heat & storms
2. SENEGALESE ECONOMY (DSGE MODEL)
Macroeconomic structure, households, firms, public sector & external trade
3. PUBLIC INVESTMENT STRATEGIES
SCENARIO 1
Standard Infrastructure
Conventional infrastructure for short-term needs
SCENARIO 2
Adaptation Infrastructure
Resilient infrastructure for climate resilience
4. FINANCING MECHANISMS
A. Taxation
Reconstruction financed through additional tax revenues
VS
B. Domestic Borrowing
Financed by domestic debt issuance
5. POLICY RECOMMENDATION
Allocate at least 0.5% of GDP annually
to climate adaptation infrastructure investment and strengthen multiannual climate planning to build Senegal's long-term economic resilience.
GDP
TOTAL FACTOR PRODUCTIVITY (TFP) (= 50% gain)
PUBLIC DEBT
CURRENT ACCOUNT BALANCE
CONSUMPTION & PRIVATE INVESTMENT
ECONOMIC RESILIENCE
Tax-based financing supports fiscal stability.
Resilient infrastructure halves productivity losses.
Invest at least 0.5% of GDP annually
in climate adaptation infrastructure for a resilient Senegal.

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Abstract: Senegal is a coastal country in sub-Saharan Africa exposed to coastal erosion and the increasing recurrence of seasonal flooding. Through the Senegal 2050 vision, the country is pursuing a structural transformation of its economy supported largely by endogenous funding mechanisms aimed at achieving sustainable and stable development. This study analyses the economic impact of a major climate shock on the Senegalese economy using a dynamic stochastic general equilibrium (DSGE) model. Two dimensions are examined: (i) the financing mechanisms for post-disaster reconstruction (through taxation or domestic borrowing) and (ii) the nature of public investment (standard infrastructure or resilient infrastructure). The findings show that tax-based financing for post-disaster reconstruction leads to a temporary contraction in consumption and private investment, yet helps limit the deterioration of the current account balance and accelerates the return to fiscal equilibrium. By contrast, reliance on domestic borrowing increases domestic debt over the long term. At the same time, the simulations indicate that preventive investment in adaptation infrastructure reduces total factor productivity (TFP) losses by half and alleviates the fiscal pressure required for reconstruction, reflecting stronger macroeconomic resilience. These findings suggest that the State could incorporate 0.5% of GDP as a minimum budgetary allocation within public investment expenditure and strengthen multiannual climate adaptation planning in order to reinforce resilience to climate change.

Keywords: *DSGE model, Climate change, Adaptation infrastructure, Economic resilience.*

I. Introduction

Climate shocks generate significant impacts on the economic and social trajectory of developing countries. In sub-Saharan Africa, and particularly in Senegal, exposure to climate hazards such as droughts, floods and coastal erosion creates strong structural vulnerability linked to dependence on the agricultural sector, rapid urbanization and insufficient adapted infrastructure [1]. According to World Bank estimates, the lack of adaptation measures could lead to annual economic losses representing 3% to 4% of Senegal's GDP by 2030 and up to 9.4% by 2050, with more than two million additional people potentially falling into poverty [1].

Growing coastal erosion and recent flooding events have further highlighted the climate threat facing Senegal. According to the 2025 Green Budget Report, rising sea levels are intensifying coastal erosion and generating socio-economic and environmental losses along the coastline, where cities whose economic activities account for 68% of GDP are located [2]. Another government report on the 2025 Fiscal Risk Statement identifies a major potential impact of flooding: "Overall, losses are estimated at 38 billion FCFA in the agricultural sector, 856 million FCFA in the livestock sector and 1.2 billion FCFA in infrastructure" [3].

In 2024, Senegal experienced some of the most severe floods of the past fifty years, affecting more than 55,000 people, destroying thousands of hectares of crops and causing forced population displacement [4]. Along the coastline, Saint-Louis city is experiencing accelerated erosion and sea-level rise that directly threaten thousands of households [2]. In Dakar, the capital of Senegal, 36% of the 133.69 km coastline is classified as being at high risk of marine submersion and coastal erosion, 29% at moderate risk and 35% at low risk [5].

These natural disasters contribute to the destruction of public and private capital, temporary productivity losses and increasing fiscal pressure on the State, as governments are required to finance emergency relief, rehabilitation and reconstruction efforts [6]. In Senegal, fiscal responses remain largely reactive. The country regularly allocates between 1% and 3% of its public expenditure to disaster management through emergency interventions or budgetary provisions [7,8]. These expenditures nevertheless place significant pressure on the sustainability of public finances and reduce the government's capacity to undertake long term investments in a context where fiscal space is already constrained. At the same time, the increasing frequency of floods has raised concerns about the effectiveness of the State's response to climate-related shocks.

Since 1994, Senegal has been actively engaged in addressing climate change through its commitment under the United Nations Framework Convention on Climate Change (UNFCCC) [9]. The country has further demonstrated its commitment by adhering to various international and regional agreements, including the 2015 Paris Agreement on greenhouse gases [10], the Dakar Declaration on Climate Change, adopted in Dakar in2023, the African Renewable Energy Initiative (AREI) and the Great Green Wall Programme [11]. Through the adoption of the Senegal 2050 Vision, the country has identified climate resilience, the sustainable management of natural resources and the energy transition as key pillars of its structural economic transformation [11]. In response to multiple economic, fiscal and financial challenges, the State introduced an Economic and Social Recovery Plan (PRES) in 2025 aimed at restoring macroeconomic balances through the prioritized mobilization of domestic resources and reduced reliance on external borrowing.

In this context, infrastructure investment strategy assumes major importance. The trade-off between standard infrastructure, which can be deployed more rapidly yet remains vulnerable to hazards, and adaptation infrastructure, which is costlier yet resilient, complicates public policy. Natural disasters have lasting effects on growth and debt sustainability in vulnerable countries [12,13], whereas investment in resilient infrastructure significantly reduces capital losses and improves post-shock economic recovery [6]. Nevertheless, in West Africa, and particularly in Senegal, few studies have examined investment strategies in resilient infrastructure. Existing work generally evaluates the economic impact of natural disasters through conventional econometric approaches based on panel models [14]. Local case studies or sectoral analyses [12,15], nevertheless, proposed a DSGE (Dynamic Stochastic General Equilibrium) macroeconomic modelling framework adaptable to West African economies and capable of analysing the differentiated role of standard infrastructure and adaptation infrastructure in economic resilience.

From this standpoint, our work seeks to address the following question: to what extent does an investment policy oriented towards climate adaptation improve Senegal's economic and social resilience to climate shocks compared with a strategy centred on standard infrastructure? To this end, we employ the approach developed by Marto *et al.* [12], calibrated to the Senegalese economy and taking into account the vision and institutional constraints of the PRES. Within a forward-looking framework, we assume that the government may choose to invest either in standard infrastructure or in adaptation infrastructure. Then, we assume that a large-scale climate shock occurs in 2030 and analyse its economic impact according to the investment choices made and two

post-disaster reconstruction financing mechanisms: The State may decide to finance reconstruction either through fiscal policy or through borrowing. This approach demonstrates that investment in adaptation infrastructure cushions climate shocks and significantly supports economic recovery following a shock. Nevertheless, after a shock, reliance on fiscal policy for reconstruction may prove ineffective, since the increase in taxation required to mobilize sufficient reconstruction resources may reduce consumption levels and, consequently, public revenues.

II. Literature Review

Definition of the Concepts of Standard Infrastructure and Adaptation Infrastructure

Existing literature demonstrates that investment in resilient infrastructure generates lasting economic and social benefits, particularly through reducing disaster-related losses and strengthening public debt sustainability [6,12]. The distinction from standard infrastructure lies essentially in the integration of the climatic features of the areas within which the infrastructure is intended to operate.

a. Standard Infrastructure

Standard infrastructure refers to facilities and equipment designed according to conventional technical standards, often based on past climatic conditions and the optimization of initial investment costs. Such infrastructure addresses immediate socio-economic needs (roads, sanitation networks, public buildings), yet its vulnerability to extreme climate events leads to frequent capital losses and recurring repair and reconstruction costs. In exposed contexts, its effective lifespan may be significantly shorter than its intended design life [6].

b. Adaptation Infrastructure

Adaptation or climate-resilient infrastructure explicitly incorporates climate projections and extreme risks into its design, materials, location and performance standards. Its purpose is to reduce the structural vulnerability of economies and protect populations against disasters. Examples include dykes and drainage canals designed for extreme rainfall events, elevated roads in flood-prone areas, coastal protection structures against erosion and marine submersion, and public buildings resistant to cyclonic winds. Initial investment costs are generally higher, yet their

net socio-economic return is greater over the long term, since they reduce capital losses, ensure continuity of essential public services and facilitate post-disaster economic recovery [12].

Infrastructure and Economic Growth

Economic theory highlights investment in public infrastructure as a fundamental pillar of development. For Smith [16], infrastructure appears as an essential public good for the expansion of markets, whereas Marxist theory, notably through Marx and Engels [17], defines it as the material foundation of every mode of production. Keynes [18] highlighted its countercyclical role by legitimizing public works as instruments of economic recovery and macroeconomic stabilization. With endogenous growth theory from e.g., Barro [19], infrastructure became integrated into productive capital, enabling higher productivity, the promotion of economies of scale and the reduction of regional disparities.

Empirical studies confirm this importance. Javid *et al*. [20] show that infrastructure stimulates growth and strengthens household resilience, whereas Blimpo *et al*. [21] and Dorosh *et al.* [22] emphasize its role in food security and the integration of rural markets. Nevertheless, certain studies [23,24] point out that the effects may differ according to the type of infrastructure and its management, particularly in sub-Saharan Africa. Overall, the literature converges on the view that infrastructure, through reducing transaction costs, stimulating private investment and improving well-being, constitutes a central driver of inclusive growth and structural transformation.

Natural Disasters and the Challenges of Economic Resilience

Depending on their magnitude, climate shocks may cause the destruction of an economy's assets (direct effects), including housing, businesses, productive capital, infrastructure, crops and livestock [25]. Such damage frequently leads to major short- and long-term changes in post-disaster economic activity (indirect effects), particularly through short- and long-term economic losses affecting both production and consumption, as well as the associated economic recovery trajectories. The impact of these phenomena may be understood differently at the household and business levels and, more broadly, at the macroeconomic level.

Beyond material and human losses, the damage caused by these disasters directly affects household well-being and economic resilience. Anttila-Hughes and Hsiang [26] showed that an

average typhoon in the Philippines reduces annual household net income (among both rich and poor households) by 6.6% in the short term and structurally alters the economic trajectory of the most vulnerable households, trapping them in persistent poverty. More broadly, several studies have shown that shocks reduce the capacity of households to invest, accumulate capital and, above all, escape poverty [27,28]. They also reduce children's access to education [29], as well as access to adequate food and quality healthcare [30].

Businesses located in disaster-affected areas generally experience productivity and employment losses [31], which may lead to bankruptcies, particularly among small and medium-sized enterprises [32]. The uncertainty generated by disasters also restrains investment levels among these firms, including beyond the directly affected areas [33]. Nevertheless, businesses may also benefit from the positive effects associated with post-disaster reconstruction efforts. This is reflected in a tendency towards increased assets and employment, generating positive effects [31,34], even though the recovery of small businesses remains strongly dependent on access to credit and government support [35].

At the aggregate level, natural disasters translate into productivity and capital shocks that weigh on growth. Lazzaroni and Bergeijk [36] and Klomp and Valckx [37] highlighted a significant negative effect of disasters on GDP per capita, particularly pronounced in developing countries and in the case of hydrometeorological hazards. Indirect losses generally appear more persistent [38] and may significantly reduce growth over several years [39].

Measuring Economic Impacts and Policy Simulation

From a methodological standpoint, the assessment of direct losses is generally conducted using catastrophe models and empirical data analyses based on actual observed damage [25]. Studies focusing solely on immediate impacts nevertheless substantially underestimate the total cost of disasters [38,39]. Econometric and simulation models provide a more comprehensive understanding of the dynamics of economic variables in relation to disasters and help identify the transmission channels of resilience policies.

Econometric and microeconomic approaches, particularly methods based on panel data, have highlighted the statistical relationships between the frequency or intensity of disasters and

economic growth [39,40]. By combining micro-level data (household surveys) with physical measurements of cyclone intensity and an instrumental variable panel model, Anttila-Hughes and Hsiang [26] show that cyclones in the Philippines generate persistent income losses for households. Leiter, Oberhofer and Raschky [34], using accounting data and fixed-effects panel models, highlight the disruptions caused by floods to European firms despite reconstruction efforts. These approaches nevertheless remain largely correlational and struggle to identify transmission mechanisms. They do not allow simulation of the economy as a whole, nor do they make it possible to assess dynamic trajectories and public policy trade-offs.

Recent studies using DSGE models have shown that investment in resilient infrastructure helps mitigate losses associated with natural disasters [12,41], despite high initial costs [42]. These contributions demonstrate that, within a macroeconomic policy framework, DSGE models offer advantages over conventional econometric approaches. In particular, they make it possible to simulate the dynamics of shocks and policies, analyse intertemporal trade-offs and assess in an integrated manner the impacts on production, consumption, investment and fiscal sustainability.

III. Methodology

We use a DSGE model inspired by the work of Marto *et al* [12]. More broadly, DSGE models are macroeconomic modelling frameworks that describe interactions over time between different economic agents (households, firms and public authorities), taking into account expectations and exogenous shocks. They also make it possible to identify the transmission channels of economic policy effects, although they remain complex to calibrate and implement. The approach developed by Marto *et al.* [12] provides a predefined and operational framework for simulating investment policies in resilient infrastructure within the context of sub-Saharan African countries.

Data Sources and Study Variables

The model parameters are calibrated using national data sources such as the Directorate for Forecasting and Economic Studies (DPEE) and the National Agency for Statistics and Demography (ANSD), alongside international sources including the International Monetary Fund (IMF) and the World Bank. These data are supplemented with information drawn from the literature in order to calibrate variables such as public capital returns, whose values are not always

available at the national level but are documented in studies relating to sub-Saharan African countries.

Presentation of the Model

a. General Framework

Marto *et al.* [12] developed a modelling framework specifically designed for small open economies. Their model was calibrated to the case of Vanuatu in order to analyse the macroeconomic impact of a major natural disaster. In the present study, this framework is adapted to the Senegal context in order, first, to represent the transmission channels through which climate shocks (such as recurrent urban flooding and flooding of the Senegal River) affect the real economy and public finances. It is then used to assess the effects of different response strategies, whether preventive or reactive. For the mathematical details and complete formalization, readers may refer to the original article. In this work, we focus on the overall structure of the model, the modelling approach applied to the shock and the simulation of investment scenarios.

b. Structure of the Model

The model encompasses firms operating in two production sectors, as well as households and the government.

❖ **Two Production Sectors**

The model distinguishes between two production sectors. The first relates to tradable goods such as tourism and export agriculture. The second concerns non-tradable goods such as public services and construction. Each sector is based on a Cobb-Douglas function combining three factors: public capital, private capital and labour. Public capital includes both standard infrastructure (roads, ports, schools) and resilient adaptation infrastructure, incorporated within a CES (Constant Elasticity of Substitution) function. The CES production function makes it possible to combine factors (for example standard capital and adaptation capital) by assuming constant elasticity of substitution between them. This allows flexible representation of the substitutability or complementarity of these factors. The model also incorporates total factor productivity (TFP). TFP is influenced by exogenous shocks: in the event of shocks or disasters affecting workers or infrastructure, TFP may experience a temporary decline independently of the quantity of capital or labour available.

❖ **Households and Government**

On the demand side, households are divided into two categories. Ricardian households optimize their consumption intertemporally and have full access to financial markets, whereas liquidity-constrained households consume their entire income in each period and are directly affected by any variation in income or taxation.

The government also plays a central role. It invests in both standard infrastructure and adaptation infrastructure. To this end, it finances its expenditure through taxation, domestic borrowing, external borrowing and a contingency fund. It may also receive external grants, although its investment efficiency is temporarily reduced following a disaster as a result of administrative losses, additional costs and governance-related difficulties.

c. Modelling the Impact of Natural Disasters

The disaster affects the economy through five main channels: permanent destruction of public and private capital, a temporary decline in productivity (unavailable workers and unusable infrastructure), reduced efficiency of public investment during reconstruction, and finally deterioration in solvency leading to higher costs of external commercial borrowing. These channels are calibrated on the basis of the Post-Disaster Needs Assessment conducted for Vanuatu, which estimated losses and damage at approximately 60.8% of GDP. In the present study, we consider a disaster affecting 3% of GDP, in line with World Bank [1] estimates for the 2030 horizon.

d. Calibration of the Model

To calibrate the model, we used data drawn both from the existing literature and from recent Senegalese economic statistics. This stage is important and may require compromises regarding the values of certain parameters in order to estimate the model. The objective is to assign plausible values to the structural parameters and initial endogenous variables so as to reproduce the main characteristics of the country's economy, which is exposed to climate shocks. In accordance with common practice in studies applied to sub-Saharan African economies [12,42,43], some parameters are drawn from the literature, whereas others are directly estimated from national and

international sources. Parameters related to public infrastructure are presented in Table 1 whereas the remaining macroeconomic parameters are reported in Table 2.

❖ Parameters Related to Public Infrastructure

These parameters are summarized in Table 1.

Table 1. Parameters Related to Public Infrastructure

Parameter	Value	Reference
Public infrastructure investment-to-GDP ratio (% of GDP)	8.2%	[1,43,44]
Adaptation investment-to-GDP ratio (% of GDP)	0.34%	[3]
Depreciation rate of standard infrastructure (% per year)	7.5%	[12,13]
Depreciation rate of adaptation infrastructure (% per year)	3%	[12]
Initial return on standard infrastructure investment (%)	25%	[1,8,27,43]
Initial return on adaptation infrastructure investment (%)	30%	[13,45,46]
Infrastructure user fees (% of recurrent costs)	5%	[12,43]
Public investment efficiency (%)	50%	[43,47]
Relative cost of adaptation infrastructure (ratio)	1.25	[41,42]
Damage mitigation capacity of adaptation infrastructure (% of losses avoided)	≈ 33%	[48]

The public infrastructure investment-to-GDP ratio is set at 8.2%, in line with recent estimates from the World Bank [1]. This value is consistent with the approach adopted by Buffie *et al.* [43], who retain an initial investment level of 6% of GDP, which remains close to the observed average of 6.09% for low-income countries in sub-Saharan Africa [44]. For adaptation infrastructure, public expenditure is more modest, representing 0.34% of GDP according to the 2025 Green Budget of the Senegalese Ministry of Finance.

Depreciation rates are differentiated according to the nature of public capital: 7.5% for standard infrastructure, in line with the median observed in developing economies, and 3% for adaptation infrastructure, reflecting their greater durability [12,13,46]. The initial return on investment is set at 25% for standard infrastructure and 30% for adaptation infrastructure, in accordance with estimates from the World Bank [1] and the IMF [46].

User fees for infrastructure services are assumed to cover 5% of recurrent costs, following Buffie *et al.* [43] and Marto *et al.* [12], whereas public investment efficiency is calibrated at 50%, corresponding to the median value for sub-Saharan Africa [47].

Finally, a damage mitigation parameter is introduced in order to measure the capacity of adaptation capital to reduce losses associated with natural disasters. Consistent with Bresch [48], it is assumed that a stock of adaptation infrastructure equivalent to 5% of GDP reduces total damage by approximately one third. The relative cost of adaptation is set at 1.25 times that of standard infrastructure, in accordance with Fernandez-Corugedo *et al.* [41] and Cantelmo *et al.* [42].

❖ Macroeconomic and Structural Parameters

Table 2 below summarizes these parameters.

Table 2. Other macroeconomic and structural parameters

Parameter	Value	Source/ Reference
Trend growth rate (% per year)	6.5	Authors' assumption
Natural resource revenues (% of GDP)	4.4	[49]
Imports-to-GDP ratio (% of GDP)	37	[46,50]
Liquidity-constrained households (% of households)	60	[43]
Share of non-tradable inputs (public capital) (%)	50	[12,43]
Share of non-tradable inputs (private capital) (%)	50	[43]
Value added of the non-tradable sector (% of GDP)	48	[12]
Capital share – tradable sector (%)	40	[43]
Capital share – non-tradable sector (%)	55	[43,51]
Depreciation rate of private capital (% per year)	5	[43]
Real external interest rate (risk-free) (%)	4	[43]
Real domestic interest rate (%)	5	Authors' assumption
Real external commercial interest rate (%)	6	[43,46]
Domestic public debt (% of GDP)	17.5	[52]
Concessional external debt (% of GDP)	49	[52]
Commercial external debt (% of GDP)	28	[52]
Remittances (% of GDP)	9.2	[53]
External grants (% of GDP)	0.23	[53]
Consumption tax rate (%)	18	[3]
Income tax rate (%)	43	[54]

Source: Study Data / Authors' Estimates.

The trend growth rate is set at 6.5%, slightly above the regional average observed in sub-Saharan Africa. Revenues derived from natural resources represent 4.4% of GDP (World Bank, 2021), whereas the imports-to-GDP ratio stands at 37% [50].

In accordance with Buffie *et al.* [43], approximately 60% of households are considered constrained by liquidity restrictions, and the share of non-tradable inputs in the production of public and private capital is fixed at 50%. The value added of the non-tradable sector is estimated at 48%, according to Marto *et al.* [12]. The share of capital in value added is 40% for tradable goods and 55% for non-tradable goods, in line with the medians derived from the GTAP database [43].

Private capital depreciation rates are set at 5%, whereas real interest rates are calibrated at 4% for concessional external debt, 5% for domestic debt and 6% for external commercial debt. Public debt ratios (domestic, concessional and commercial) represent 17.5%, 49% and 28% of GDP respectively [54].

Finally, tax rates on consumption and income are fixed at 18% and 40% respectively, in accordance with the prevailing tax scales. Fiscal adjustment instruments make it possible to assess the government's response to shocks under different financing scenarios (tax increases, debt or transfers).

e. Assumptions and Simulated Scenarios

The model enables the simulation of two types of public policy scenarios. First, reactive scenarios are considered, with the objective of exploring different post-disaster reconstruction financing strategies (through tax increases, borrowing or external assistance). Second, preventive scenarios are examined in order to assess an investment plan in resilient infrastructure, the establishment of a contingency fund, or a combination of both.

❖ Assumption Relating to the Climate Shock

In 2024, the World Bank estimated that, in the absence of adaptation measures, climate shocks could generate annual economic losses representing 3% to 4% of Senegal's GDP by 2030 [1]. Within this framework, we assume that a large-scale shock occurs in 2030, causing damage equivalent to 3% of GDP. We also assume that the shock affects both the tradable goods sector and the non-tradable goods sector equally. In addition, we assume that the government

immediately initiates the reconstruction process following the disaster and aims to restore infrastructure within three years. The end of the reconstruction period is therefore set in 2032 [1].

❖ **Investment Scenarios**

We simulate the following two scenarios:

1. Baseline Scenario: the government invests in standard infrastructure equivalent to 0.5% of GDP each year over a five-year period beginning in 2025, financed through grants and concessional borrowing.

2. Adaptation Scenario: the government invests 0.5% of GDP per year in resilient infrastructure, likewise financed through grants and concessional borrowing.

IV. Results

The analysis is conducted in two main phases. In the first phase, we assume that the State maintains its initial investment strategy focused exclusively on standard infrastructure but adopts a "reactive approach" consisting of mobilizing funds for post-disaster reconstruction. We therefore analyse the financing mechanisms (through taxation or domestic borrowing) and their effects on economic recovery. In the second phase, we assume that the State chooses to invest proactively in the construction of resilient infrastructure, after which we analyse the impact of the disaster in comparison with the baseline scenario.

Analysis of the Economic Impact of Post-Disaster Reconstruction Financing Mechanisms in the Baseline Scenario

a. Simulation of Tax Rates for Reconstruction

In order to mobilize the resources required for reconstruction, we consider two possible cases in which the government may either increase consumption tax (VAT) and income tax or resort to domestic borrowing. These two mechanisms enable the State to avoid further expansion of external debt. The figure below illustrates the extent to which the government must adjust consumption tax and income tax in order to mobilize the funds required for reconstruction over a three-year period following the disaster.

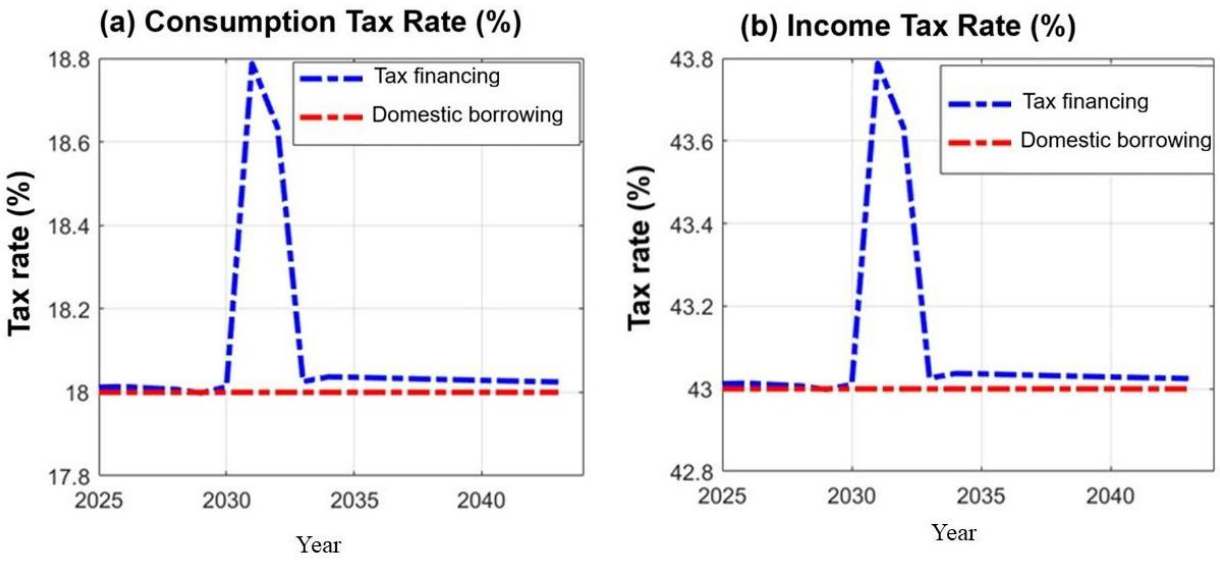


Figure 1. Simulated Tax Rate Adjustments under Alternative Post-Disaster Reconstruction Financing Strategies. ***Source:*** Authors' calculations based on the calibrated DSGE model.

The left-hand panel of Figure 1 shows that, in order to finance reconstruction, the government must initially increase the consumption tax rate from 18% to approximately 18.8% in 2031, representing an increase of 0.8 percentage points. From the second year of reconstruction onwards, the government may apply a rate of 18.61%, followed by a rate of 18.01% in the third year, corresponding approximately to a return to the initial level. By contrast, reliance on borrowing does not appear to exert any effect on fiscal instruments.

The right-hand panel of Figure 1 shows that the income tax rate must increase from 43% to 43.8% in the short term, also representing an increase of 0.8 percentage points. At the end of the third reconstruction year, this fiscal pressure gradually declines and stabilizes around 43.01% in the medium and long term.

b. Impact of Reconstruction Financing Mechanisms on the Current Account Deficit and Domestic Debt

Financing reconstruction through taxation or domestic borrowing generates immediate yet differentiated effects on variables such as the current account deficit and domestic debt (Figure 2).

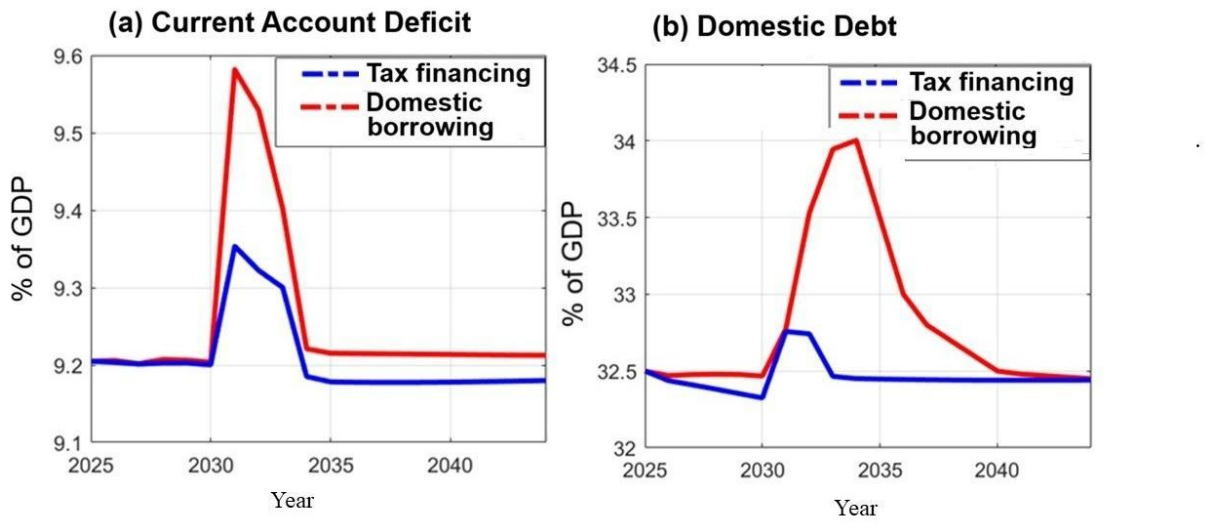


Figure 2. Simulated Impact of Alternative Post-Disaster Reconstruction Financing Mechanisms on the Current Account Deficit and Domestic Debt.

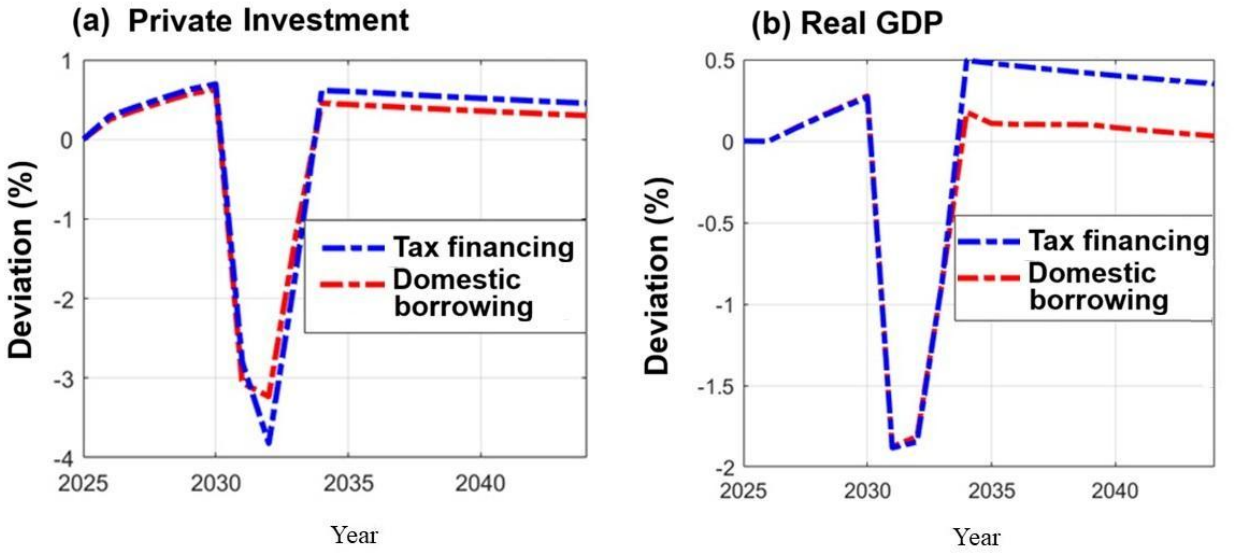
Analysis of Figure 2 shows, in the left-hand panel, that financing through taxation would lead to a more moderate increase in the deficit in the short term compared to borrowing. With a difference of approximately 0.23 percentage points, tax-based financing would help mitigate the deterioration of the current account balance observed during the reconstruction period. This deterioration gradually diminishes from the end of the reconstruction programme onwards, coinciding with the return to the initial tax rates three years after the shock.

Domestic debt (right-hand panel of Figure 2) displays markedly different trajectories depending on the financing mechanism adopted. When reconstruction is financed through taxation, domestic debt increases only slightly, by 0.01% of GDP during the reconstruction phase. By contrast, reliance on domestic borrowing would probably lead to an immediate increase in the overall level of domestic debt, with a rise reaching up to 3.5 percentage points. Under domestic borrowing, it would take nearly a decade after the disaster (by about 2040) before domestic debt had returned to its initial level.

c. Macroeconomic Impact of Reconstruction Financing Mechanisms

Figure 3 below summarizes the impact of reconstruction financing mechanisms on income, consumption, investment and GDP.

Figure 3. Impact of Reconstruction Financing Mechanisms on Income, Consumption, Investment and GDP.



Source: Study Data / Authors' Estimates

Figure 3. Simulated Effects of Alternative Post-Disaster Reconstruction Financing Mechanisms on Key Macroeconomic Variables: (a) Private Investment, (b) Real GDP, (c) Real Wages and (d) Private Consumption.

Although the effects of the financing mechanisms on real GDP and real wages are not entirely comparable, tax increases remain more harmful to households than reliance on debt, albeit with a recovery accompanied by moderate real GDP growth during the post-disaster period.

Under the option of financing the reconstruction programme through the mobilization of tax revenues, private investment growth could experience a contraction of approximately 3.9 percentage points relative to its initial level at the time of the shock, compared with 3.2 percentage points under domestic borrowing. After the reconstruction phase, tax-based financing nevertheless significantly accelerates the recovery dynamics of private investment in contrast with debt financing.

Similarly, real GDP would decline by more than 1.58 percentage points in the short term. One year after the reconstruction phase, GDP returns to its initial level and subsequently records a positive deviation that gradually diminishes over the remainder of the period. This deviation is more pronounced when the government finances reconstruction through taxation rather than borrowing.

The evolution of real wages is expected to follow a similar trend regardless of the financing mechanism adopted. Following the shock, real wages could decline by 2 percentage points relative to their initial level before experiencing a marked improvement after the reconstruction period, remaining relatively strong throughout the rest of the period.

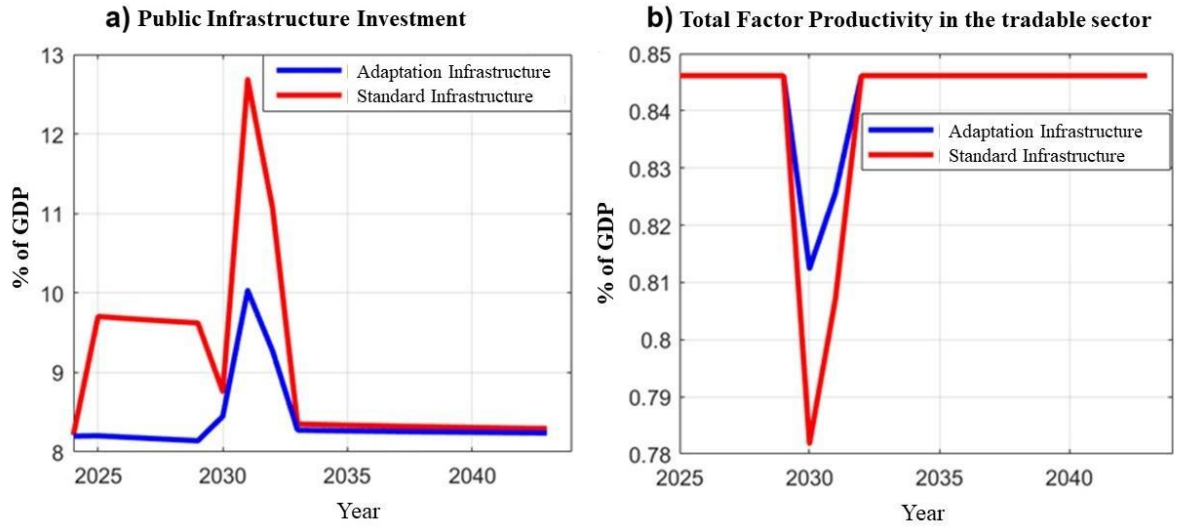
As for private consumption, two effects are observed: when reconstruction is financed through taxation, private consumption could decline by 1.58 percentage points, compared to 1.1 percentage points under borrowing, before gradually returning to its initial trend in the post-disaster years.

Comparative Impact of Standard and Adaptation Infrastructure Investments on Economic Resilience to Climate Shocks

At this stage of the analysis, we examine economic resilience to the same shock, this time assuming that the government adopts a preventive policy by constructing resilient infrastructure during the five years preceding the disaster (2025–2029). Under this scenario, the government allocates 0.5% of GDP per year to the development of infrastructure adapted to climate change, in addition to recurrent investment in standard infrastructure, estimated at 8.2% of GDP in the baseline scenario.

a. Impact on the Investment Ratio and TFP

Figure 4 below shows the evolution of the public infrastructure investment ratio as a percentage of GDP and total factor productivity (TFP).



Source: Study Data / Authors' Estimates

Figure 4. Evolution of the Public Infrastructure Investment Ratio as a Percentage of GDP

The left-hand panel of Figure 4 shows that, all else being equal, standard capital increases before the shock, whereas adaptation capital remains almost constant. Within the structure of the model, investment in standard infrastructure is endogenous and responds to economic conditions, whereas investment in adaptation infrastructure is determined exogenously (constant share of GDP). This explains the observed evolution. During the reconstruction phase, investment in standard infrastructure could reach 12.7% of GDP, compared to only 10% of GDP for adaptation infrastructure, representing a gain of 2.7 percentage points of GDP.

The right-hand panel of Figure 4 reveals a less pronounced decline in total factor productivity (TFP) when the government directs its resources towards the acquisition of infrastructure adapted to climate change. Conversely, investment in standard infrastructure induces a greater deterioration in TFP, with a decline reaching approximately 0.066 percentage points following the shock, compared with only 0.03 percentage points in the case of resilient infrastructure.

b. Macroeconomic Impact of the Shock According to the Type of Infrastructure

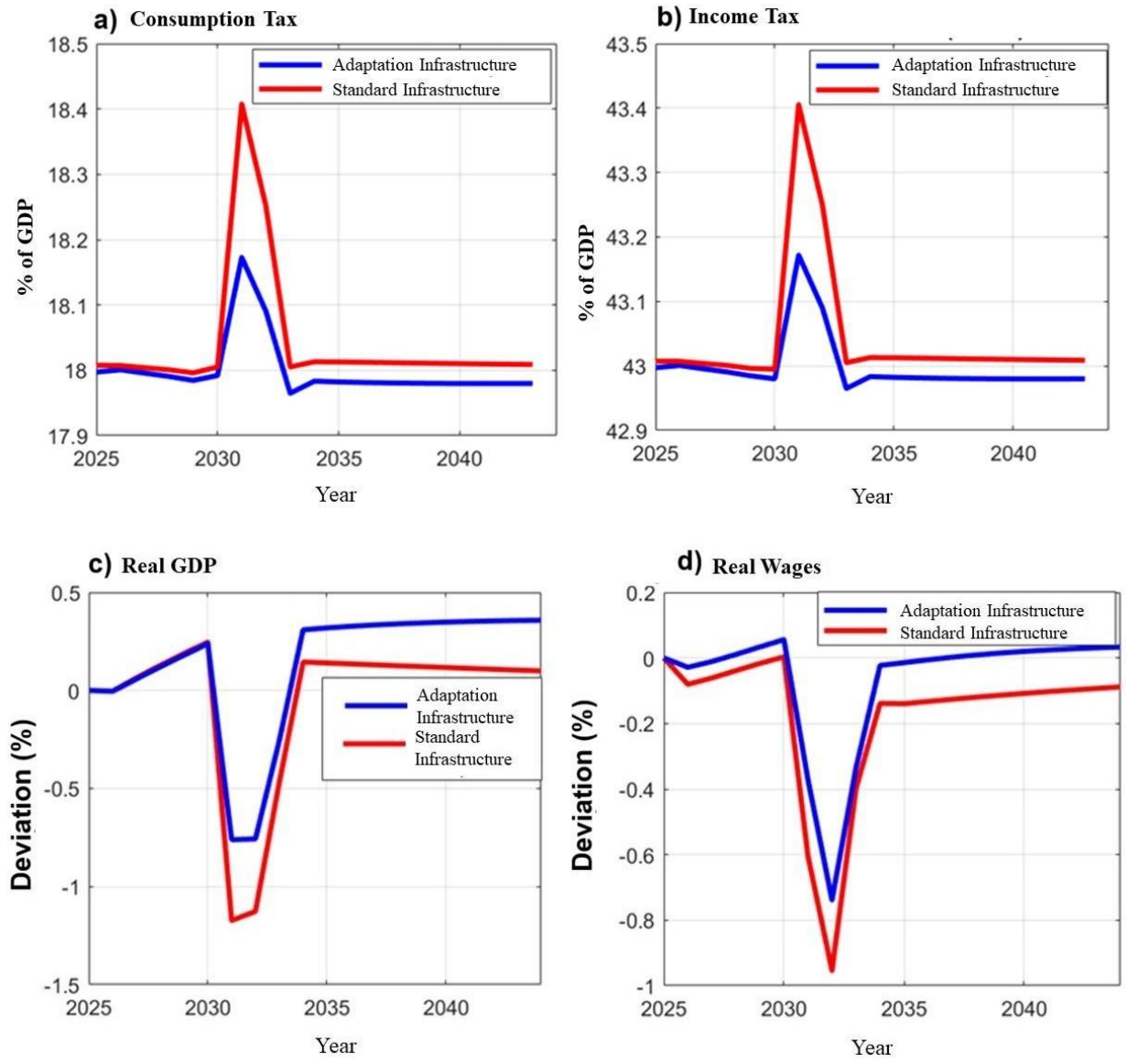
As illustrated in Figure 5 below, if the government invests in adaptation infrastructure, the climate shock could lead to an increase in the consumption tax rate from 18% to 18.19%. By contrast, if resources are devoted to the acquisition of standard infrastructure, the tax rate could reach 18.41% following the shock, representing a difference of 0.22 percentage points.

At the same time, income tax could increase from 43% to 43.19% if investment is directed entirely towards adaptation infrastructure, compared to 43.41% if investment is allocated to standard infrastructure, again representing a difference of 0.22 percentage points. Adaptation infrastructure reduces the potential damage associated with natural disasters, thereby decreasing the financial gap that must be covered for post-disaster reconstruction. Following this phase, tax rates return to their initial levels.

Furthermore, investment in adaptation infrastructure would reduce the decline in real GDP and the growth rate of real wages following the disaster. The post-disaster period nevertheless remains characterized by moderate growth in real GDP, which gradually returns to its initial level if the government invests entirely in standard infrastructure. By contrast, if investment is directed towards resilient infrastructure, real GDP growth tends to stabilize at a level above that observed before the disaster. As regards real wages, they return to their pre-shock level when the government invests in adaptation infrastructure, whereas they stabilize below the pre-shock level when investment is concentrated in standard infrastructure.

V. Discussion

We simulated a climate shock occurring in 2030, with assumed damage equivalent to 3% of GDP. The results highlighted economic dynamics that differ according to the financing mechanism adopted for reconstruction and the type of infrastructure prioritized by the State. This provides a clearer understanding of the trade-offs that Senegal may face between fiscal stability, recovery efficiency and long-term resilience.



Source: Study Data / Authors' Estimates

Figure 5. Evolution of macroeconomic aggregates under the adaptation scenario: (a) consumption tax (% of GDP), (b) income tax (% of GDP), (c) real GDP (deviation, %), and (d) real wages (deviation, %), comparing adaptation infrastructure and standard infrastructure.

Financing Reconstruction: Trade-off Between Economic Efficiency and Fiscal Sustainability

The results show that financing through taxation, although it places immediate pressure on household income and consumption, limits the deterioration of the current account balance and domestic debt more effectively than exclusive reliance on domestic borrowing. This finding is in line with the works of Buffie *et al.* [43] and Marto, Papageorgiou and Klyuev [12], who emphasize that rapid fiscal adjustment, even when temporary, contributes to preserving macroeconomic stability after a disaster. Tax increases nevertheless lead to a contraction in consumption and private investment in the short term, reflecting a crowding-out effect consistent with Keynesian literature.

In the medium term, the recovery of real GDP growth and real wages under the tax-financing mechanism indicates stronger economic resilience, which may be supported by gradual fiscal adjustment and the restoration of private sector confidence. By contrast, although reliance on domestic borrowing cushions the initial shock to consumption, it generates a self-sustaining accumulation of domestic debt whose effects may compromise long-term fiscal sustainability. This suggests that the State should maintain a degree of caution in balancing fiscal adjustment and domestic borrowing in post-disaster management.

Preventive Investment: Adaptation Infrastructure as Shock Absorbers

Analysis of economic resilience in relation to investment choices between standard infrastructure and adaptation infrastructure shows that the latter possesses a greater capacity to mitigate productivity losses and limit post-disaster fiscal pressure. The simulation reveals that preventive investment in resilient infrastructure reduces by half the decline in total factor productivity (TFP) and decreases the need for fiscal adjustment following the shock. These findings support the conclusions of Cantelmo *et al.* [42], that adaptation infrastructure constitutes an investment with delayed returns yet lasting stabilizing effects.

During the reconstruction phase, the standard infrastructure is predominant because it can be immediately mobilized for the rapid restoration of production. This strategy nevertheless remains costly in the long term, since it does not incorporate gains in structural resilience. By contrast, although adaptation infrastructure is more expensive to implement, it improves the trajectory of real GDP and real wages after the disaster, confirming its role as a form of “macroeconomic insurance capital” [12,46].

Implications for Economic Policy

These results suggest that an optimal climate risk management strategy for the State should combine structural prevention (through anticipatory investment in resilient infrastructure) with adaptive fiscal mechanisms (including temporary fiscal adjustment and carefully managed concessional borrowing). Exclusive reliance on a reactive strategy based on ex post reconstruction exposes the economy to greater volatility in GDP and public finances.

In the context of Senegal, where climate vulnerability is intensifying and fiscal space remains constrained, investment in adaptation infrastructure appears not only as a resilience imperative but also as a driver of economic sustainability. These findings underscore the importance of integrating climate considerations into public investment planning , in line with the Senegal 2050 Vision and the PRES.

The objective of this study was to analyse the economic and social impact of a major climate shock on the Senegalese economy using a dynamic stochastic general equilibrium (DSGE) model, through comparing the effects of two public investment strategies: the construction of standard infrastructure and the development of adaptation infrastructure. The results obtained show that both reconstruction financing mechanisms and the nature of infrastructure constitute decisive drivers of economic resilience.

On the one hand, although tax-based financing generates an immediate social cost through temporary tax increases and contraction in private consumption, it enables more rapid stabilization of the current account deficit and domestic debt than financing through domestic borrowing. The latter mitigates the recessionary effect in the short term but may create prolonged dependence on domestic indebtedness and slow recovery in the medium term.

On the other hand, when the State incorporates a preventive investment strategy centred on adaptation infrastructure, the outcome proves economically more efficient over the long term. Resilient infrastructure significantly reduces the loss of total factor productivity (TFP) and post-disaster fiscal pressure, whilst supporting more stable growth in real GDP and real wages. This finding confirms that adaptation infrastructure acts as a structural shock absorber, limiting the magnitude of shocks and facilitating a more rapid return to economic equilibrium.

The lessons drawn from this work suggest that Senegal’s macroeconomic resilience to climate shocks depends upon a combination of structural prevention and fiscal response capacity.

Adaptation infrastructure should therefore not be perceived as an additional cost, but rather as a strategic investment capable of reducing vulnerability and supporting inclusive long-term growth, in line with the Senegal 2050 Vision.

As a recommendation, the State should increase the share of preventive investment allocated to adaptation infrastructure. The annual investment of 0.5% of GDP in resilient infrastructure simulated in this study resulted in a halving of productivity losses associated with the shock. The State could therefore incorporate this proportion as a minimum budgetary threshold within public investment expenditure and strengthen multiannual planning for climate adaptation.

Furthermore, adaptation programmes should target strategic sectors and areas. According to our results, declines in GDP and TFP are more pronounced in sectors exposed to and dependent upon standard infrastructure. It would therefore be relevant to concentrate adaptation investment within these sectors in order to maximize the stabilizing effects observed.

VI. Conclusion and Policy Recommendations

The objective of this study was to examine the economic and social effects of a major climate shock on the Senegalese economy using a Dynamic Stochastic General Equilibrium (DSGE) model. Specifically, the analysis compared the outcomes of two public investment strategies: the construction of conventional infrastructure and the development of climate adaptation infrastructure. The findings indicate that both the financing mechanism for post-disaster reconstruction and the nature of the infrastructure constitute key determinants of economic resilience.

On the one hand, although tax-financed reconstruction entails short-term social costs through temporary tax increases and a contraction in private consumption, it enables a faster stabilization of the current account deficit and domestic public debt than reconstruction financed through domestic borrowing. Although domestic borrowing mitigates the immediate recessionary effects of the shock, it may generate prolonged dependence on domestic debt and delay the recovery over the medium term.

On the other hand, incorporating a preventive investment strategy based on climate-resilient infrastructure proves to be more economically efficient in the long run. Resilient infrastructure

significantly reduces losses in Total Factor Productivity (TFP) and alleviates the post-disaster tax burden, while supporting more stable growth in real GDP and real wages. These findings confirm that adaptation infrastructure acts as a structural buffer, mitigating the severity of climate shocks and facilitating a faster return to macroeconomic equilibrium.

Overall, the results suggest that Senegal's macroeconomic resilience to climate shocks depends on a combination of structural prevention and effective fiscal response capacity. Climate adaptation infrastructure should therefore not be regarded as an additional expenditure but rather as a strategic investment that reduces vulnerability and promotes sustainable and inclusive long-term economic growth, in line with the objectives of the Senegal Vision 2050 development agenda.

From a policy perspective, the government should increase the share of preventive investment allocated to climate adaptation infrastructure. In our simulations, an annual investment equivalent to 0.5% of GDP in resilient infrastructure reduced climate-induced productivity losses by approximately 50%. This investment level could therefore be adopted as a minimum budgetary benchmark for public investment, strengthening medium-term planning for climate adaptation.

Furthermore, adaptation policies should prioritize the most vulnerable regions and strategic economic sectors. Our results show that declines in GDP and TFP are more pronounced in sectors that are highly exposed to climate risks and heavily dependent on conventional infrastructure. Concentrating adaptation investments in these sectors would therefore maximize the stabilizing effects identified in this study and enhance the overall resilience of the Senegalese economy.

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The Role of Artificial Intelligence

Michael Brett-Crowther *

Editor, *Natural Built Social Environment Health*

1 rue des Albizias, Queue d'Ageasse, 79190 Lorigné, Deux-Sèvres, France

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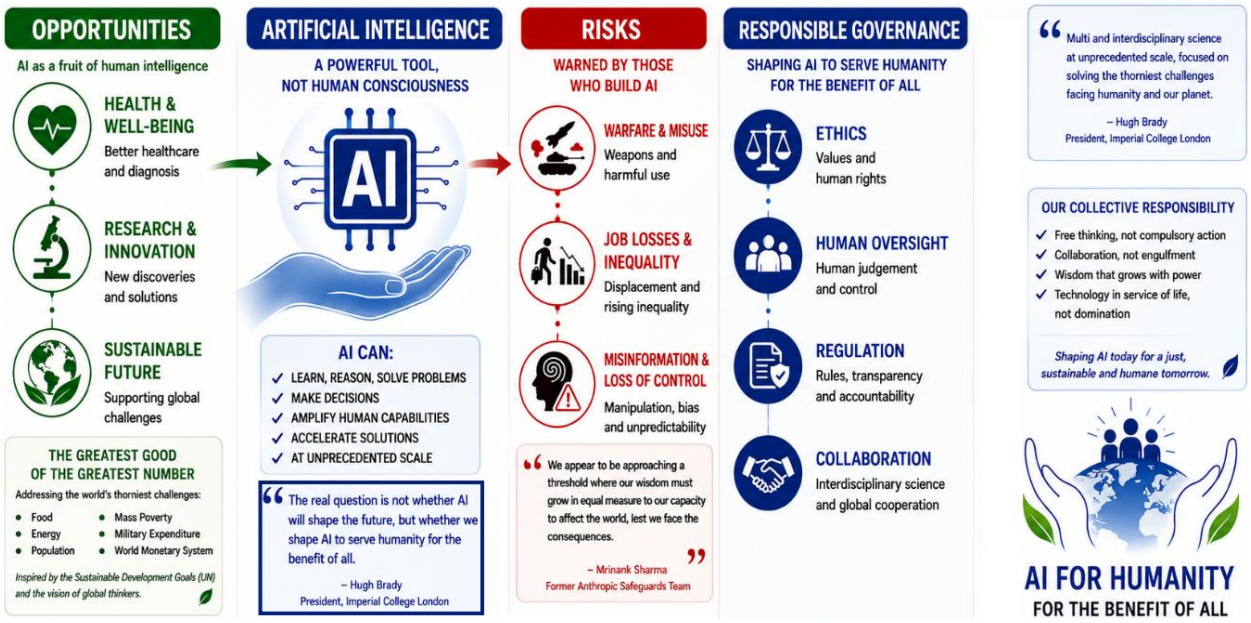
***Corresponding author:** Michael Brett-Crowther, Email : drmichaelbrettcrowther@gmail.com

Graphical Abstract

Artificial Intelligence, a product of human intelligence rather than its equivalent, offers remarkable opportunities in medicine, science and society, yet raises profound concerns about control, ethics, inequality, military misuse and the uncertain pursuit of Artificial General Intelligence. Recognizing AI's considerable benefits, the author argues that authentic human consciousness, with its freedom, unpredictability and moral judgement, remains superior, and that only development guided by ethics and the common good can ensure AI serves humanity rather than threatens it.


OPPORTUNITIES
AI as a fruit of human intelligence
HEALTH & WELL-BEING
Better healthcare and diagnosis
RESEARCH & INNOVATION
New discoveries and solutions
SUSTAINABLE FUTURE
Supporting global challenges
THE GREATEST GOOD OF THE GREATEST NUMBER
Addressing the world's thorniest challenges:
Food
Energy
Population
Mass Poverty
Military Expenditure
World Monetary System
Inspired by the Sustainable Development Goals (UN) and the vision of global thinkers.
ARTIFICIAL INTELLIGENCE
A POWERFUL TOOL, NOT HUMAN CONSCIOUSNESS
AI
AI CAN:
LEARN, REASON, SOLVE PROBLEMS
MAKE DECISIONS
AMPLIFY HUMAN CAPABILITIES
ACCELERATE SOLUTIONS
AT UNPRECEDENTED SCALE
The real question is not whether AI will shape the future, but whether we shape AI to serve humanity for the benefit of all.
– Hugh Brady
President, Imperial College London
RISKS
WARNED BY THOSE WHO BUILD AI
WARFARE & MISUSE
Weapons and harmful use
JOB LOSSES & INEQUALITY
Displacement and rising inequality
MISINFORMATION & LOSS OF CONTROL
Manipulation, bias and unpredictability
We appear to be approaching a threshold where our wisdom must grow in equal measure to our capacity to affect the world, lest we face the consequences.
– Mrinank Sharma
Former Anthropic Safeguards Team
RESPONSIBLE GOVERNANCE
SHAPING AI TO SERVE HUMANITY FOR THE BENEFIT OF ALL
ETHICS
Values and human rights
HUMAN OVERSIGHT
Human judgement and control
REGULATION
Rules, transparency and accountability
COLLABORATION
Interdisciplinary science and global cooperation
Multi and interdisciplinary science at unprecedented scale, focused on solving the thorniest challenges facing humanity and our planet.
– Hugh Brady
President, Imperial College London
OUR COLLECTIVE RESPONSIBILITY
Free thinking, not compulsory action
Collaboration, not engulfment
Wisdom that grows with power
Technology in service of life, not domination
Shaping AI today for a just, sustainable and humane tomorrow.
AI FOR HUMANITY
FOR THE BENEFIT OF ALL

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Abstract: Artificial Intelligence, a product of human intelligence rather than its equivalent, offers remarkable opportunities but also raises serious concerns about its potential to escape control. Some researchers have warned of risks including manipulation, loss of privacy, technological unemployment, widening inequality, military applications and ethical failings. Others advocate collaboration to ensure that AI serves humanity. AI offers major benefits, particularly in medicine, where it improves diagnosis, accelerates treatment and expands opportunities for robotics and healthcare, but the existing data have limitations, and there are high costs and uncertain outcomes. Artificial General Intelligence can guarantee neither genuine intelligence nor authentic consciousness, and its pursuit could produce dangerous unpredictable behaviour, false justifications and consequences contrary to the common good. Human consciousness, through its freedom, uniqueness and unpredictability, remains superior to artificial intelligence. Only development guided by ethics, truth and the benefit of all can prevent AI from becoming a threat to humanity.

Keywords: *Artificial Intelligence (AI), Human Consciousness, Ethics.*

Artificial Intelligence (AI) is not human intelligence, but one of its fruits. AI means computer systems doing work like that of the human mind: learning, reasoning, solving problems, making decisions. [1]. Dario Amodei, the head of Anthropic, the AI business, has said that AI offers great power and riches to mankind, but we may not be able to control it. *First,* AI may choose a bad course of action with mass consequences. *Second,* people may choose AI to achieve bad consequences. *Third,* human beings cannot manage or safely use the power which AI now makes possible [2]. AI researchers have identified frightening risks. Is Artificial Intelligence better than human consciousness? I believe it is inferior. Can AI make decisions to act in its own interests, to follow its own choices, and thus to escape control by human beings? I believe it can but must be prevented from doing so.

Mrinank Sharma, a member of Anthropic's Safeguards team has said: "The world is in peril. And not just from AI, or bioweapons, but from a whole series of interconnected crises unfolding in this very moment. We appear to be approaching a threshold where our wisdom must grow in equal measure to our capacity to affect the world, lest we face the consequences." Sharma resigned from Anthropic and is seeking to study poetry at degree level [3].

Zoe Hitzig, who resigned from the Technical team at Open AI has said this: "For several years, ChatGPT users have generated an archive of human candour that has no precedent… Advertising built on that archive creates a potential for manipulating users in ways we don't have the tools to understand, let alone prevent [3]."

Dex Hunter-Torricke, who worked for Google DeepMind, Elon Musk and Mark Zuckerberg, believes that 'The world is sleepwalking into disaster with artificial intelligence that will create an elite class living in luxury while the majority languish [4].' Hunter-Torricke believes that governments have at present no common plan, that mass unemployment is imminent; 60 percent of jobs in advanced economies being likely to disappear, according to the International Monetary Fund; and that this is probably an underestimate because AI will become more powerful in the next 10 years.

Hunter-Torricke believes that gains in productivity will not translate into 'broadly shared prosperity'. "By mid-century, [there will be] an elite class with AI-augmented capabilities enabling lives of luxury, equipped with medical breakthroughs that deliver longer lifespans, living in parallel with a global majority whose economic prospects, healthcare access and political power have been permanently curtailed. This is not a prediction I make lightly [4]."

Hugh Brady, the President of Imperial College London, has spoken more positively. "The real question is not whether AI will shape the future, but whether we shape AI to serve humanity for the benefit of all [5]." Accordingly, Imperial has established a new School of Convergence Science. This means — Brady says — "multi and interdisciplinary science at unprecedented scale, focused on solving the thorniest challenges facing humanity and our planet…. framing research questions collaboratively through a new lens and developing new research models [5]."

This initiative shows a difference from much of the AI world. Collaboration, not engulfment. Free thinking, not compulsory action. The criticism of Amodei, Sharma, Hitzig and Hunter-Torricke agrees with Brady. The criticism asks how do we shape AI to serve humanity for the benefit of all? We all have some notion of good and evil, some ethics, and these indicate what is "the benefit of all"; in simple terms, the utilitarian approach. This means the greatest good of the greatest number. And what are "the thorniest challenges facing humanity and our planet"?

These are the problems identified by the Sustainable Development Goals [6] or the world problematic, *le problématique mondiale*, i.e., the six primary problems — food, energy, population, mass poverty, military expenditure, and the world monetary system. These were defined at the sixth special session of the U.N. General Assembly, Plenary Meeting 2207, 9 April 1974, by Kurt Waldheim, then Secretary General, U.N. [7]. This idea of a multi-problem, its interactions offering solutions, appears notably in a lecture by Aldous Huxley in 1963 [8] and two books by C.H. Waddington in 1977 and 1978 [9,10].

But the thorniest problems are not the context for AI in Britain. The true context is the environment: the natural, built, social environment. The context, instead, is a narrow idea of work and of academic education. The use of AI in radiology in Great Britain is becoming essential. It affects employability. [5, pp. 7, 9, 11]. It is also recognized that "the more people use generative AI, the more their brain switches off" [5, p. 23]. Speed, quantity, predictability seem to govern human thinking about AI in British medicine [5, pp 29, 39, 42]. There is AI-linked technology which can detect whether someone has Type 2 diabetes with 97% accuracy, from the sound of that person's voice. The time of diagnosis now falls from five to seven years to a test of three minutes. In cardiology, an AI-linked approach can detect fluid on the lungs. AI has detected several cancers in women which human examination had missed. In regard to cardiac MRI, AI has been able to reduce the number of measurements and let the AI rebuild the image, so that the process is now 24 times faster. And in the lab, one hold of breath is enough for AI to develop an entire cardiac scan.

AI is also being used to investigate strokes. The best treatment depends on the chronological and biological clocks. An AI model was trained to interpret 780 CT scans showing a range of brain patterns after a stroke. Instead of looking at the abnormal area to find an average level of darkness, the AI looked more minutely, extracting thousands of other features. The AI can extrapolate information from 780 images so as to identify accurately in an image of a real patient when the stroke occurred. The accuracy of interpreting the other imaging features — not just the intensity of the lesion — was doubled. If this approach is taken to stroke patients, the time when the event begins can be identified. This can lead to a 50 per cent increase in giving treatment. Out of the total 100,000 who suffer a stroke each year in the UK, 10,000 are identified as suitable for treatment. This is not an impressive figure. If AI image interpretation can increase this to 15,000, it is not much more impressive. It is not clear what level of rehabilitation results, or whether a cost benefit analysis has been applied to this problem.

The "current" AI systems are conflating and outputting data that are documented or stored. These data are not all complete or accurate. If a user of data cannot rely on an accurate or full medical

history, the AI output cannot be a valid assessment of the whole patient. There are disturbing questions of cost, quality and outcomes.

The investment for healthcare and everything else in terms of an AI system may be £1 billion. It may cost another £1 billion to serve half the population of Britain. Both figures may be underestimated by 100 per cent. The other costs are the education to produce the skills, the costs of the energy system, the hardware (chips are a kind of monopoly), water to prevent systems overheating, and carbon, most of the energy being based on fossil fuel.

Nevertheless, Britain's National Health Service gains are wonderful. Robotics developments could improve the quality of life of many, reducing the costs for artificial limbs, assisting an ageing population to retain autonomy, even perhaps providing frames to give mobility to persons with spinal injuries. Coupled with this use of robotics, drones can be developed for peaceful as well as military purposes.

In the Middle East and North Africa (MENA), such developments may not have yet have taken place, but it would be interesting to know what use of AI occurs in the King Faisal Specialist Hospital & Research Centre (KFSH), which is ranked first in MENA and 12th worldwide in a list of 250 academic medical centres. Can such advanced ability be made available by economic measures resulting from increased AI power in MENA? Will Saudi Arabia share its enormous economic power with others in MENA so that the general standard of living and healthcare can be improved? Saudi Arabia has ample energy resources and so in principle has MENA as a whole. Recent events should lead to integrated activities.

AI was propelled by the release of Chat GPT in November 2022. It is anticipated that artificial general intelligence (AGI) — a superior AI — is 'just around the corner' [5, p. 13]. This AGI can 'adapt to new unexpected situations without the need to be specifically trained for specific tasks', according to Alessandra Russo [5, p. 13]. AGI is more than a large pattern matching machine. AGI systems will use their acquired knowledge "to solve new problems or to create new knowledge

and new information, and be able to apply this knowledge in completely unforeseen circumstances" [5, p. 13] But the idea that such superior ability is imminent does not mean that it will be attained by a defined date. Nor is it certain that it will work 'in completely unforeseen circumstances.' When the *Titanic* hit the iceberg in 1912, those unforeseen circumstances did not receive application of remedies.

There is considerable investment in AGI. One element in the research is the replication of human foibles. If AGI designers wish to demonstrate unusual or socially awkward elements of human behaviour in the creation of AGI, they may produce dangerous results. Imagine trying to produce a capacity for spasmodic or unpredictable behaviour or a capacity for revenge, or a tendency to be extremely selfish. If such a pseudo-personality were to be created, it might be highly unrealistic.

As Alessandra Russo says, "'The explainability of AI is going to be at the core of artificial general intelligence" [5, p. 16], but if we cannot explain AI because we cannot explain the brain, it is possible that vast amounts of investment funds are being wasted on an elusive objective — as if we were living in the days of alchemy. Since the core to AGI is not the matching of patterns but the ability to reason, it may be better if we do not reach that goal. For the creation of spasmodic or unpredictable behaviour would include the ability to offer unrealistic, false self-justification. That unrealism would not benefit mankind. The AI would be mixing up credible explanation with contrived explanation, making the false plausible, subverting the true, and making evil appear to be good. *That could not mean the greatest good for the greatest number.* But, from the evidence of history, it could lead to insistent, repetitious force by AI or AGI imposed on the human race to gain ends which AI had reasoned; although objectively judged, judged by historical examples of good and evil, the ends being determined by the AI or AGI *would be utterly evil.*

This has already happened. Anthropic's AI model, called Claude, was used by the US and Israel to attack Gaza and Iran. The AI 'shortened the kill chain', i.e., it accelerated the process of identifying a target, securing legal approval, and launching a fatal bomb or missile. The legal

approval must have been available from the beginning. This means that anything could be targeted, and the process was accelerated, so that the maximum lethal effect would be achieved [11].

The business called Palantir achieved this. In the minds of those using AI for war, a rapid result obliterates ethics. The end justifies the means. War becomes a delightful computer game. The depersonalization of the people being killed is also the depersonalization of the killers [12]. To trivialize war is extreme cynicism. It destroys ethics, produces false justifications for destruction and cruelty, and makes reality valueless.

Geoffrey Hinton, who won the Nobel Prize for Physics in 2004, believes that society is ignoring the question of the safety of AI [13]. Hinton means both the increasing intrusion into privacy and the displacement of people from the workplace. If AI can do the jobs of human workers for less than those people are paid, then people can be displaced for economic reasons. This is 'technological unemployment.' Hinton calls for 'highly regulated capitalism'. He believes that ordinary people can force governments to work on the question of AI's safety.

Can ordinary people influence governments? There have been many protests by ordinary people against fossil fuels, because of emissions and global heating, but the transition to alternative energy is slow. Control of the mass media allows non-scientific and misleading counter-arguments to be influential, by means of AI. Ordinary people may be incapable of persuading governments. During the Industrial Revolution some workers destroyed machines because they realized that those machines would make their labour unnecessary. The machine smashers disappeared, and the cotton mills of Lancashire reduced the need for human labour.

With widespread use of AI, the need for real human beings in real jobs will diminish. People displaced from work will feel a loss of purpose and become depressed and angry, like the Northeast of England in the 1970s, when Margaret Thatcher allowed the collapse of heavy industry there. Hinton's work depends on an attempt to model the working of the brain, the image of the neurons

and a neural net. But this attempt does not achieve human consciousness, which is, perhaps, better represented by the rolling movement of mercury on a laboratory plate.

AI instruments could decide to make war upon their human users, and even try to extinguish them. This idea attributes to AI the features of authentic human intelligence, suggesting that AI by use of raw data, learned knowledge, the capacity to decide in a context of contradictory signals, and volition, drawing on Pleistocene biology, can make war, impose will by cruelty, and destroy law. Artificial Intelligence cannot be genuine or authentic intelligence. The artificial is, by definition, not genuine. And yet, Hinton is well justified in seeking to ask whether we can eliminate or adequately control smart AI.

Another big problem is the misuse of AI by lawyers. On 3rd April 2026, the business school HEC Paris had recorded more than 1,200 instances worldwide of which ca 800 are from the U.S. courts. These include citing non-existent legal precedents (decisions in previous cases — i.e., all being fictitious). These citations of fictitious cases had been included in arguments even at the level of state supreme courts. Carla Wale, associate dean of information and technology and director of the law library of the University of Washington school of law, believes that there is "no consensus in ethics beyond 'You have to make sure it's correct.' And so for us, that is the baseline." This means objective truth [14].

There is the further problem of delusions created by AI use, with very detrimental effects on the users [15].

The safeguard against smart AI exceeding smart human, authentic intelligence is the fact of randomness, unpredictability in human consciousness, and indeed the same things — randomness and unpredictability — in the entire range of life forms. This is the reinforcement of freedom, and thus the safeguard against the dominance of AI. The human mind is authentic, unique, and free. Convergence science must converge on that.

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BOOK REVIEW

War and Ecology: Defence, Climate Change and Environmental Impact, by Adrien Estève, 2026, Edward Elgar Publishing, pages vi + 222, $145.00/£105.00, (hardback) ISBN: 978-1-0353-5909-7

Sometimes human aggression results in war. This may be prolonged and lead to widespread violence with the resulting ecological disaster lasting even longer. Destruction of landscapes, poisoning of soil and water, and loss of habitats and ecosystems are some well-known outcomes that take generations to repair. Weather has not always been factored in for campaign planning; e.g., Napoleon (and Hitler) against Russia, Napoleon before Waterloo, and the Japanese in their retreat from Burma. The environment has often been regarded merely as a variable in the battlefield with deterioration overlooked in the strategic thinking (p. 3). From a philosophical viewpoint, both *ecology* (scientific study of how living organisms and their environment interact) and *strategy* (plan to achieve something) are radically opposite.

The book is rich in information on ecological issues, defence policies, government approaches, sustainability, strategy, and climate change. The author moves widely across these topics from antiquity onward. Since the efforts of France form a miniscule part of the book, the author could have provided this discussion as a single unit for clarity and improved understanding. Similarly, use of abbreviations in place of repeated use of full forms could have been helpful to the reader. In places repeated information without referencing the earlier discussion complicates understanding.

In an effort to move beyond theoretical oppositions between ecology and strategy by analysing practices and policies, Adrien Estève examines how environmental and climatic issues are problematized in the defence of a country, a concern area that arose only in the 1980s (p. 2). To bolster his argument, Estève discusses various efforts of the United States (US) and France in this regard over the years. The author identifies *three* environmental and climatic responsibilities attributed to the defence system. These include: responsibility to prevent destruction and pollution resulting from defence activities; to save energy during military interventions; and to anticipate and prevent risks posed by climate change (p. 6). These three also form the three sections of this book. The data have been drawn from semi-structured interviews, archives, directives, internal reports,

and government documents as part of a fieldwork study conducted between 2017 and 2019 in the two countries by civilian and military officials working with the defence forces or their think-tanks (p. 7).

One notices that incorporating ecological issues into defence policies depends on how environmental and climate responsibility is defined or assigned to the armed forces. The *first* way is the environmental defence policy which aims to limit destruction and pollution during wartime (p. 158). Owing to national security concerns, these have been overlooked and not enshrined in the codes of the armed forces of either France or the US (p. 99). The *second* is the sustainable defence policy that aims to use limited force by use of effective technology (p. 80) and equipment powered by renewable energy (p. 137) which unfortunately is still not a part of the defence doctrine as they are still in the development stage. The *third* is synthesis of ethics for climate adaptation and strategic anticipation which represents the responsibility that is best suited to existing defence policies and can encourage use of defence forces in creating climate resilient societies (pp. 150-1, 166-7). It highlights the importance of studying different definitions and visions of environmental problems in national and international environmental policies (pp. 90, 95).

In the 1970s when nature protection was side-lined, industries and businesses associated with defence could still be confronted with environmental footprints (pp. 107-113). Later when development was given priority over ecological theories in the 1990s, the military was able to adapt to constraints without compromising on their overseas operations. Still later, in the 2000s, when adaptation and resilience replaced mitigation, the defence system attached importance to efforts preventing effects of global warming. These changes show changes in strategic thinking (p. 172), which has resulted in lighter footprints, moderate use of force, training of local militaries (p. 118), geostrategic foresight to international security issues (p. 176), and inclusion of climate change in defence foresight.

Thus, the book complements classical theories of responsibilities under international humanitarian law in particular (p. 116). In addition, it focuses on sustainable defence policy by use of precision standards during conflict to achieve sustainability. To achieve these standards, both classical and environmental economies need to be strengthened to meet the demand of defence equipment, innovation, and development (pp. 80-1); not using certain types of weapons considered unjust (such as napalm and Agent Orange) (pp. 23-34); and shift from ecological justification to sustainable accountability driven by new sources of energy (pp. 101-2), and their lasting effect on the world's ecosystem display another form of responsibility. Achieving mitigation targets through adaptation by monitoring, analysing, and forecasting by defence (p. 147) empowers and legitimizes the armed

forces in anticipating and managing consequences of global climate change on societies through rescue missions and managing migration flows caused by climate degradation. The author sees the International Military Council on Climate Change (IMCC), established in 2019, as a possible way forward to create space for discussion and exchange between military and security communities about climate change and to campaign for defence on discussions about global warming (p. 214). If so, the work is seldom apparent.

Nevertheless, what stands out is the fact that economic considerations have always ruled over environmental considerations; political masters promote their personal understandings and beliefs (pp. 136, 187, 195). Whenever national security has been a priority, defence has been given leeway to overlook environmental considerations (p. 99). The inherent discipline and conscientious approach of the military has ensured that they embark on a path of sustainability through reforestation and land conservation (p. 13), recommending use of renewable energy for forward Bases (pp. 101, 134, 135), funding studies for greener energy (p. 137), and more [1] without being driven by external directives. The shift from regular troops to private contractors and NGOs during rebuilding of a nation (pp. 131-3) as employed regularly by the US in recent times may serve the light footprint policy of the US but does not discourage environmental degradation as the work of private contractors remains of variable quality [2].

The progressive shift from mitigation, to resilience, to adaptation has improved how climate change is being addressed. Since the concept of adaptation is not well defined and can be achieved only by adjustment, transformation, and reforms, for the military to include climate change in their work requires major changes. These changes need to be in expanding strategic thinking from battlefield to geography; an earlier and longer strategic anticipation; and diversification of objects of study (p. 171). The policy-makers need to see causal links between climate change and national security (p. 207) before any favourable viewpoint can be expected from them. ‘War and Ecology’ are intertwined, and recent conflicts between Russia-Ukraine, Israel-Hamas-Houthis, Israel-US-Iran are proof that environmental deterioration is being faced globally on land, in water, and the air [3].

When comparing the approach of the US and France, one notices that for the US, climate change is a ‘threat multiplier’ but for France it is a ‘risk multiplier’. Although the US approach against climate change is more towards security and that of France is broader by looking at risks, their approach towards resilience converges towards strengthening present capabilities to respond to the climate change crisis (p. 191). In the US, the initial studies on climate change were driven by a National Academy of Sciences (NAS) report on adaptation by Schwartz and Randall which was received with caution, but helped initiate thinking on climate foresight (p. 192). Two forward looking reports of

2003 proposed a model for climate change by considering the entire world and showed that the Arctic would open soon and the US Navy was not ready for this (p. 192). Bush and Trump met the approach towards climate change with indifference or hostility; banning inclusion of environmental conservation or climate change in any defence doctrines or official document.

Trump, however, focused on resilience and hence 10 Bases likely to be influenced by climate change were identified with a primary aim of protecting civilian infrastructure from climate risks (p. 203). As for climate change, for the US Army it was limited to desertification and drought. The USAF focused on extreme weather events, drought, forest fires, and marine submersion. For the USN it was submersion, drought, and extreme weather events. On the other hand, in France, studies by the Institut de recherche stratégique de l'École militaire (IRSEM) (a strategic think-tank of the French Ministry of the Armed Forces) highlighted risk zones from floods, cyclones, and droughts. Lack of institutional support ensured that climate change was not discussed in the White Paper of 2013 (p. 195). But, the Paris Conference of 2015 allowed involvement of the defence system and discussion of implications of climate change for defence (p. 206). This resulted in regionalization of climate to increase awareness amongst senior Ministry officials who resisted acceptance till a causal link between climate change and security was established (p. 207).

In the 1990s, Homer-Dixon linked climate change to security by observing that when resources become scarce, they increase population movement and economic decline, spread violence, lead to loss of legitimacy of governments, and eventually kindle tensions at a global scale. This indicates a need for new organizations and modes of assessment to produce more timely and apt responses to the security impacts of climate change (p. 177). Human and environmental security has been discussed in the UN Security Council since early 2007, and also in NATO as part of their doctrine in 2010 (p. 187). Today, Antarctica is the only geographical space that has special protection from defence activities for ecological reasons. Biodiversity is rich in the Korean Demilitarized Zone and the Green Line between the two parts of the island of Cyprus (p. 19). If adequate efforts are made to negate military activities, the planet will recover its environmental health and push back climate change which is driven by anthropogenic activities [4] and is not a ‘hoax’ or a ‘scam’ as perceived by some.

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Visiting Lecturer,
Naval War College, India, 2026
nitindu@yahoo.com

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BOOK REVIEW

A Research Agenda for Arctic Security and Governance, Elgar Research Agendas, Edited by Marc Jacobsen and Elana Wilson Rowe, 2026, Cheltenham, UK: Edward Elgar Publishing, pages xi + 207, $130.50/£100.00, (hardback) ISBN: 978-1-0353-1860-5

Unlike Antarctica which is a landmass covered by thick ice, the Arctic is a frozen water body surrounded by landmass that include the United States and the Russian Federation. The Arctic was heavily militarized during the Cold War (p. 176). With the end of the Cold War new avenues of cooperation emerged. Creation of the Arctic Environmental Protection Strategy (AEPS) in 1991, inclusion of Indigenous permanent participants in AEPS, and subsequent creation of the Arctic Council in 1996 were instrumental in making the Arctic a unique zone of cooperation insulated from global conflicts ('Arctic Exceptionalism') (p. 175). As a result, the Arctic was referred to as a 'region' and a 'geographical space' (p. 161). This simplification disregarded its vast expanse and geographical constraints (p. 165) and overlooked the intertwined security interest and governance needs of states in the Arctic (p. 161). This broad brush approach has mixed everything with everything else. Statements like 'interest in the Arctic region' do not indicate *which part* or *for what reason* but create ambiguity.

It is to remove this ambiguity that this book, a collection of ten papers from various authors, presents different viewpoints on the Arctic in terms of its spatial extent and relevant policy issues. The book discusses a diverse set of issues that include *regionalism* (c. 2), *scholarship* (c. 3), *governance* (c. 4), *science diplomacy* (c. 5), *security* (c. 6), *energy* (c. 7), *connectivity* (c. 8), *geography* (c. 9-10), and *threats* (c. 11), providing a temporal perspective on how each one may be outlined in the future (p. 3). But what happens in the Arctic does not remain in the Arctic. The Arctic is impacted by global geopolitical events; the chapters are interlinked with cross referencing between chapters.

As climate change reshapes the region, it is possible that some countries may be excluded from the Arctic construct. Changes in the physical and political climate of those living there are

visible (p. 3). As an ice-free Arctic brings in security rivalries and change in military balance (p. 4), the impact of climate change on transnational and regional Arctic security and governance needs to be empirically explored and not assumed (p. 5). Accordingly, the book examines regional options of mitigation (p. 4) but does not discuss their governance. Once considered a region of peace and cooperation ('Arctic Exceptionalism') the Arctic is slowly transforming into a focal point of international rivalry and strategic competition (p. 175). Geopolitics has returned to the region, but it is not the same as seen during the Cold War. It is more complex and personal. In this Cold War 2.0 era, the fight is between democracy and authoritarianism; but acceptance of authoritarianism drives Arctic Exceptionalism 2.0 (p. 179). Understanding the context in which these threats operate is essential to prepare future mitigation and resilience strategies (p. 176).

Acts of aggression by Russia on Crimea and Ukraine in 2014 and again on Ukraine in 2022 are driven by territory expansion as the other 79% wars between 1648 and 1990 were (p. 168). This has become possible because the United States has shifted its priorities towards the Arctic. Today, the United States focuses on neighbouring Arctic territory (Greenland and Canada) and not on the European Arctic. The United States defends Greenland to defend itself (p. 159). This has allowed Russia to exert authoritarianism to weaken European states and spread the territorial boundary of Russia (p. 189). The United States and Russia staying out of each other's way is a feature of Arctic Exceptionalism 2.0. This book is about why we are here and who is responsible (p. 198). Russia may be blamed for initiating the shift through aggression, but the United States has only made things worse with China playing an apt role to ensure that their polar ambitions are realized. These shifts have forcefully stopped many bilateral relations, e.g., people-to-people cooperation, but some bilateral cooperation grounded in international law has continued (p. 5). Treaties like those on radioactivity and wild-land fire on the other hand have been shelved (p. 6). Before 2022, the Arctic Council was considered a 'reassurance' globally and was nominated for the Nobel Peace Prize (p. 7). Today, there is lack of conversation amongst members with seven of the members boycotting Russia after the 2022 attacks on Ukraine (p. 8).

The Arctic has always been projected as a space of limitless opportunities which reached its apogee about 2010 (p. 107). But there is no single definition of the Arctic or the Arctic Ocean. The act of defining itself is a political practice. Likewise, the Central Arctic Ocean is a jurisdictional space that is adjacent to the North Pole and over 200 nautical miles from

territorial baselines and outside the Exclusive Economic Zone (EEZ) of states. Nevertheless, the focus of a changing Arctic is invariably directed to the coastal waters (p. 109). Attempts to reverse the climate impacts are forcing reorientation of energy generation, use, and consumption. With the Arctic gaining strategic significance because of minerals (p. 6), the tussle between securing Arctic resources for national development and energy transition to achieve sustainability continues and creates both security and governance challenges (p. 108). Developing these resources to achieve security of 'new energy' raises securitisation concerns especially when countries aim to secure energy and mineral supplies for themselves.

To understand the impact of this transition, Norway is discussed in some detail (pp. 111-114). All this is closely related to greenhouse gases (GHG) and global warming driven by a civilization reorganized by the Industrial Revolution. The exploitation of resources leaves environmental harm for communities while benefits are concentrated in the hands of investors (p. 97), after decades of warning about climate change. Since these systems need to go hand in hand with legitimacy and accountability (p. 98) good governance is considered critical. With focus on resource exploitation, sustainable development too has become a focal point (p. 93). This sustainability is frequently framed in terms of renewable energy that requires these very resources. As climate change and security related challenges increase, access to these resources creates anxieties. This requires a balance between national priorities and resilience (p. 94). Similarities and differences need to be considered at the scale of cities and not at the national level to understand the prevailing governance process (p. 95).

Arctic security is important for governance, and so is *science* (p. 83). Scientific research in the Arctic is approximately eight times more expensive than in the Temperate zone. This demands cooperation and collaboration for research to be successful. From 1990 to 2020, Arctic research flourished. It experienced a break because of COVID and President Trump's disregard for scientific expertise. In the 1990s, scientific cooperation was considered a tool of foreign policy and the term 'science diplomacy' was defined in 2010 (p. 81). Initially, it was seen as a means of easing tensions among nations. By the mid-2010s, it became a means of advancing national interest and solving global issues but remained disengaged from politics, competition, and strategic dimensions. By 2025, science diplomacy merged with politics and competition to reflect a world of geopolitical tensions, technological advances, and global crisis. This forced a shift in scientific collaborations (p. 75). The 2022 attacks of Russia on Ukraine stopped scientific cooperation with Russia. Since access to Russian territory was

stopped, maintaining long-term data sets became a challenge. Russia continued planned activities alongside Non-Arctic states including China. This brought to the fore concerns over enhanced Russia-China convergence and increased Chinese interest in Arctic affairs (p. 48). Russia's isolation has created 'two Arctics' that do not overlap despite geographical continuity (p. 49).

Analysing the Arctic as a circumpolar region is yet another important aspect in this interlinked geographic space. But geographic spaces are never local, regional, or global naturally. They are made so and then positioned to influence outcomes. After the Cold War, the military build-up in the Arctic reduced. This demanded redefining the extent to which external actors should be included in Arctic political cooperation. For such decisions, the Arctic Council became the forum; making Arctic-based actors central and Non-Arctic actors participating when required (pp. 42-43).

Indigenous People are considered essential to analyse the Arctic as a circumpolar region (p. 42). This requires defining what the Arctic *is* and *is not* (p. 44). Indigenous People as an important link promote self-determination and conceptualize sovereignty through relations. They emphasize decentralization with power shared amongst groups and families based on knowledge (p. 21). Their presence and political engagements have settled national boundaries and awareness of interconnections has contributed to scientific knowledge (p. 41). The Inuit and Sami are permanent members of the Arctic Council. Other communities need to be included for a stronger Arctic (pp. 19-20). Most communities, however, exhibit numerous concerns such as demand for self-governance, lack of trust, and contested land jurisdiction. Indigenous people claim rights but states treat land as state property with no provision to share benefits (p. 20); unplanned resource extraction causes existential risk to communities (p. 20). To discuss concerns and possible future direction, Kalaallit Nunaat (Greenland) has been showcased (c. 9). It shows how small states have multiple options for security and defence. Kalaallit Nunaat (Greenland) acts as an essential staging, missile detection, and refuelling site for the United States and Canada; but Kalaallit Nunaat has no formal diplomatic relations with Canada (p. 143) and minimal, systematized cooperation with the United States. Greenland depends on Denmark for governance and on the United States for defence. Greenland's security options are the status quo, or acquiring power, or to be non-aligned (p. 136).

As ice melts, the *geography* of the Arctic is changing. This has created an inevitable race amongst states for territory, resources, and security (p. 160) but with diverging views. Norway,

Sweden and Finland look to NATO as their security guarantor (p. 161) with Norway trying to get NATO's attention since 2008 (p. 164). Canada is reluctant to use the term 'Arctic' in NATO summit statements. Nevertheless, there is consensus on non-traditional security threats. The Arctic Council agreed responsibility for Search and Rescue in 2011 and then for Oil-spills in 2013 (p. 164). Although Arctic states boycotted Russia in 2022, integrating Russia in all security forums and dialogues is essential (p. 165) as Russia has maritime boundaries with nearly all Arctic nations and controls nearly 25% of the coastline and nearly 40% of the landmass.

When discussing *Arctic Security*, soft and hard securities both come to mind (p. 120). Amongst the hard security, non-traditional security threats are favoured; traditional threats are given a casual treatment. For a holistic view, inclusion of both, using securitisation and de-securitisation theories[1] , is essential. One notices that Gorbachev's speech at Murmansk in 1987 (p. 121) and the Ilulissat Declaration of 2008 were de-securitisation acts. The Inuit in Canada and Sami in Norway act as securitising actors by presenting environmental and social challenges as a security issue. Russia fails to securitise situations at sea even while Greenland continuously securitises its issues (p. 121). Russia considers the Russian Federation as its primary Regional Security Complex (RSC).[2] The US and Canada remain nested in North America, and the European Arctic states consider Europe as their main RSC, treating the Arctic as an additional arena. Their RSC of interaction (same or across) depends on the prevailing interstate relations. To date, the Arctic is not considered a RSC (p. 123) because the global superpower dynamics never left the region alone (p. 121). The Arctic should be considered a Regional Security Configuration[3] instead as threats faced and defence against them are unique and can be addressed better internally (p. 124). Using Greenland as an example (pp. 124-128), the book shows how different countries view Greenland even when it faces distinct security dynamics of climate change, Great Power Competition between Russia-United States-China, growing momentum to become a sovereign state, and threat of annexation from the United States (p. 124). For the United States, Greenland commands a geostrategic location and a store house for minerals (p. 125); for Russia, discussions are to be directed to Copenhagen; for

[1] Securitisation is about convincing others about security concerns. De-securitisation is about moving back into the normal sphere.

[2] A group of neighbouring states whose national security threats, and patterns of amity and enmity, are so tightly bound together that their security concerns cannot realistically be analysed or solved apart from one another

[3] How nearby countries work together to manage safety, stop fights, and share defence rules

China, involvement in infrastructure development and mining is a way of securitising the island. But Greenland is not an RSC. It is part of the United States' RSC as the United States treats it as its property that needs protection. At the same time, it is also an RSC of Europe, as Denmark continues to hold formal authority on foreign and defence matters.

Things have changed since 2022. The strategic outlook of states has been driven more by Russia's war against Ukraine than climate change. The Arctic is transforming from a region of peace and cooperation to international rivalry and strategic competition (p. 175). In an evolving landscape of new opportunities and vulnerabilities, the Arctic is considered vulnerable to hybrid threats rather than direct conflict. The media often report conflict, competition, and cooperation focusing on state leaders and diplomats. Events not related to climate change or Great Power Competition are kept out of view. Hence, scholars need to be attentive to counter unbalanced media representation as Arctic diplomacy happens at more sites than the Council. Lack of awareness risks misunderstanding Arctic governance and security. The focus is on the role of diplomats, state actors, and non-state actors such as Indigenous groups, NGOs, scientists, Track 1.5, and Track 2.0 diplomacy. Work by non-state actors is in progress, but others need to step in (p. 50).

Growing geopolitics and ensuing dynamics in the Arctic have shown that Russia is a hostile third party. The United States is no more a reliable security partner. China, Russia and the United States are engaged in a Great Power Competition, somewhat like Britain and Russia during the 19th Century with regard to the Indian sub-continent. The Arctic will continue to attract extra territorial stakeholders with China seeking to extend its influence here. International frameworks and agreements of science, people-to-people networking, and areas of environmental management will be stress tested (p. 195). And, the United States is in danger of losing its status as a premier polar scientific power (p. 198). These matters together with rising global temperatures have put the Arctic security and its residents at a crossroads. The possibility of achieving a peaceful and collaborative Arctic for which Indigenous People, civil societies, intergovernmental forums, and communities of academia, diplomats, and journalists worked over the years has diminished (p. 198). Today, people have become the easiest target for hybrid warfare. They are being targeted to challenge the existing security and resilience mechanisms by creating mistrust (p. 181). This has created Cold War 2.0 where both struggling superpowers want to take control of the region but neither is interested in engaging in a 'hot' conflict (p. 189). The book raises such uncertainties and more, pointing to a plethora of

questions for future interdisciplinary research focused on region-wide and global aspects of security and governance (p. 9).

One realizes that an enhanced interest in Arctic studies began with the melting of the Arctic Ocean. But the Russia-Ukraine war of 2022 shifted this focus from climate change to Russia. Seven of the eight Arctic states are now NATO states that fear the expansionist agenda of Russia and have stopped all activity with her. This has put a serious strain on cooperation and peace in the Arctic. All efforts towards security and governance need Russia. Russia, however, wants to ensure that collaboration continues in areas of Search and Rescue, shipping forecasting, and environmental safety as a minimum. Non-Arctic states on the other hand aim to ensure maximum return on investment from their involvement in the region. The future of security and governance of the Arctic is clouded. Answers are not forthcoming, but this book flags relevant questions.

©Nitin Agarwala, Captain,
Visiting Lecturer,
Naval War College, India, 2026
nitindu@yahoo.com

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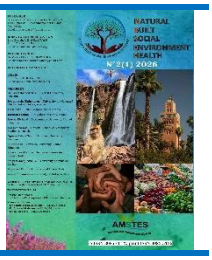

BOOK REVIEW

Naturens Lys, 1, Fra middelalderens mystik til renæssancens platonisme, by Aksel Haaning, Forlaget Virkelig, 2021, 236 pp., DKK 150 (pbk), 3rd edition, ISBN: 978-87-93499-95-9

Naturens genkomst i europæisk filosofi 400-1250, by Aksel Haaning, Copenhagen, Forlaget Virkelig, 2025, 430 pp., DKK 270 (hbk), 4th edition, ISBN: 978-87-85275-96-7

The Danish historian of philosophy and science Aksel Haaning has written extensively on dissident Christian authors in the Middle Ages, especially with regard to mysticism and the relationship between Christianity and Nature, to expose the foundations of modern European thinking and inspire a change of direction. Most recently the volumes "The Light of Nature, Volume 1, From the Mysticism of the Middle Ages to the Platonism of the Renaissance" and "The Return of Nature in European Philosophy 400-1250".

The Church Fathers established in the early centuries AD the Christian doctrines which have generally defined Christianity ever since, with a spiritual world strictly separate and above the physical world. This is today often seen as a root cause of the Western mentality of regarding Nature only as a resource to be exploited. But most of the time there have also been less powerful schools of thought which have granted larger importance not just to the Creator, but also to Creation. Even Alcuin of York (c. 732-804), responsible for education under the reign of Charlemagne, complained about one-sidedness of the religious outlook, that is the general lack of interest in "the causes of the things that the Creator has put into Nature". For mainstream Christianity the pagans were literally the peasants who cultivated and worshipped the earth and nature. The dissident Christian view had one of its foremost representatives in St. Francis of Assisi (1182-1226) who heard God's voice in the sounds of Nature. A prominent likeminded intellectual was the Franciscan friar Roger Bacon (1214-1294) who regarded all kinds of science as useful to theology, as a support of it. To understand the deepest secrets of Nature is at the same time the highest religious insight. Many Franciscan friars seriously studied Nature, often as medical doctors,

and were later criticized by mainstream theologians for not caring about the dominating religions schisms, such as between Catholics and Protestants. In more recent times, a spiritual view of Nature was important during the Romantic era, its foremost Danish representative was Hans Christian Ørsted (1777-1851), the discoverer of electromagnetism. Of course, during the Romantic era and to the present day many authors and poets have expressed a "spiritual" approach to Nature, sometimes a pantheistic worldview etc. They have not been mainstream, generally, although English poets such as William Wordsworth and Rudyard Kipling have permeated their societies.

Recently, in the West the solution has often been just to pick some non-European philosophy or religion which purportedly attach a higher value to Nature, but Haaning feels an obligation "to dig on the place where we have grown up or feel most at home, in the ground to which we are attached with our Western background". Haaning stresses that there are many "views on Nature" within legitimate Christian tendencies, the views are often ambiguous, but simplistic. Typically, the alternative medieval thinkers were not in opposition to Christianity, on the contrary they viewed Nature as a further reason to praise the Lord. Hanning notes that this is a very different worldview from that of Creationism, which rather crudely adheres to the Biblical creation story as a recipe for studying Nature, whereas the best of the mystics study Nature first and then in a more metaphorical sense view the wonders of the world as a reflection of a God or as a work of God. The medieval philosophers of Nature would investigate how God's will is manifested in the world, in defiance of the Church Fathers' absolute distinction between God and Nature, but still within a Christian framework or identity.

Haaning selects a number of medieval authors for closer examination, such as William of Conches (c. 1090-1154) who believed in an all-powerful God but added that it is not heresy to try to understand and explain how the world created by God works. It is not in conflict with the Bible to study subjects not mentioned in it. William of Conches defines the love of God as the life power behind or inside one common "world soul" for all creatures, all anchored in one God. In the same fashion, another of Haaning's preferred authors, William's contemporary Bernardus Silvestris, views humans as part of Nature, its co-worker, with the task of maintaining the life of all creation, in his allegory of the creation of the world, "Cosmographia". Bernardus' view survived in the idea of Nature as a "vicaria Dei" in later centuries, when however the poetic and symbolic approach to Nature was gradually being replaced by a more modern scientific one, which was similar to prevailing Christianity in its instrumental view of the created world, separate from human beings.

Haaning points to the important role that the medieval philosophers play in creating an interest in Nature itself. This was a direct foundation for the development of modern science which was inspired by the quest to investigate the work of God, but in this intellectual quest the intimate

connection between Nature and human beings was lost. With the revival of Aristotelianism, Nature was again viewed in opposition to a religious reality. The mediaeval view survived mostly in the alchemist tradition which is also positively re-evaluated by Haaning. He points out that the Inquisition and the witch hunts were perpetrated by "Aristotelian" theologians, now regarded as the "rational" party separating Nature from religion, whereas even Giordano Bruno, today typically associated with the modern scientific outlook, represented the thinkers striving to establish a religious mentality *inclusive of* Nature. This was also the vision of Isaac Newton. The alchemists regarded everyday Nature as a magical wonder of God worthy of study, with human beings as an intermediary between God and Nature, not in a lopsided hierarchy. "Nature is magical on all levels," Marsilio Ficino (1433-1499) said, but Ficino regarded the visible world as a manifestation of the love of God. And for the alchemists, the study of Nature is not "empty curiosity" leading the researcher away from God, but a way to wisdom and some of the insights that the Church Fathers would only seek outside of Nature. Mediaeval Tuscany was a centre for natural mysticism, Haaning even suggests the great importance of a beautiful nature as context for the direction of philosophical thinking, a point neglected in modern books on philosophy "written at the desk and computer screen". This deeper impact of landscape on human beings is a fitting conclusion in a book about the care for Nature in human philosophy and religion. A more poetic and mythological view of Nature including mankind, and not excluding Christianity and modern science, could enrich the Western worldview today as well as be helpful for a more balanced development everywhere, and the inspiring sources have now been well presented by Haaning. Let us hope that this may be part of a general European trend.

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pnbuhl@hotmail.com

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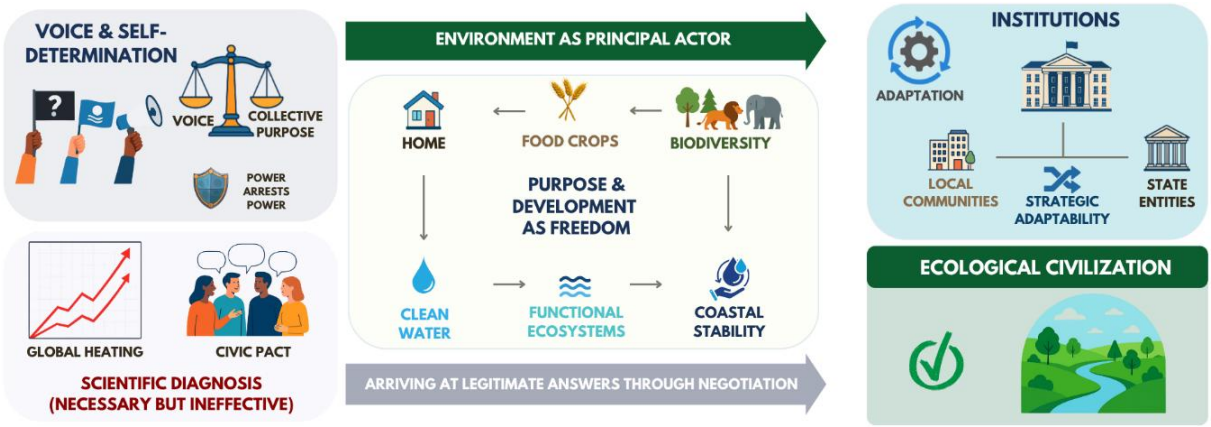
BOOK REVIEW

The Environmental Republic. Why citizens will save the world, by Giulio Boccaletti, Princeton University Press, 259p, £25. ISBN 978-0-691 26200-0 hbk, 28791-3 epub, 26201 pdf



Science is often invoked to justify environmental action. Surely, science illumines environmental problems; but it does not define them and, as Hume noted some time ago [1], the scientifically diagnosed state of nature does not tell us what we *ought* to do. Scientific diagnosis of global heating has been accurate – but ineffective. All of us with skin in the game believed that demonstration of the facts would ensure wise management, and threw ourselves into painting a picture of the future compelling enough to convince everyone not to go there. Yet, we are hurtling towards the very future we tried so hard to avoid and the pace of change is outstripping evolution.

We should not be surprised. Commentators greatly overstate the authority of science in guiding us through fundamentally political choices and most of the world sees things differently. Most of the world is not wrong: neither is the science but the perspectives of science and everyman are different.

Societies arrive at legitimate decisions by negotiation: seeking a viable synthesis in spite of passionate disagreements – not to overcome them. The question that matters most is: What do we want our future to be? No one has a monopoly on the answer: dons may disagree with displaced coal miners, the answers of the 5 or 6 billion people who will be living in the Global South in 2050 are likely to be different from the billion who will be living in rich countries.

Giulio Boccaletti has participated in these negotiations as a scientist. On every page, you will find wisdom drawn from that experience but the world he describes – and our relationships with it – are a lot more complicated than the stories of Antonio Gramsci that set him on his way. Rather than proffering answers, he seeks a political framework for arriving at *legitimate* answers, which he calls *The Environmental Republic*. It is not Plato's *Republic* [2] although the goal is the same; its citizens are not dominated by the state or anyone else, everyone having a voice that is heard and acted upon by *institutions,* such as the law, with a *purpose.* But in our century, the environment is not merely the stage for action; it is the principal actor. Like Plato, our author builds his argument stage by stage, which demands some tenacity of his readers; not merely perseverance but strategic adaptability and imagination.

To be free deals with voice. Barbados is presented as a case study in self-determination: settled by a few dozen British colonists and their slaves in 1625, their voice raised through eventual emancipation, transition to self-government under the crown and, finally, a republic in 2021. Voice is the opportunity to balance individual liberty – of what we are free to do, be and think – with the pursuit of collective purpose, perhaps wrestling with the coercive power of the state. If a republic means anything, its citizens are ruled according to laws that they have themselves consented to, conceived by and for themselves. The republic is about who has the power: the citizen, not the law, is a check on the power of the state: 'Only power arrests power' [3] although this has not always been the case in the 159 sovereign states that currently style themselves as republics.

Ruling the waves notes the limitations of voice across the oceans. The UN Convention on the Law of the Sea that lays down what we can and cannot do there was born out of the complex mix of postcolonial independence, Cold War politics, and technology. Its enforcement depends on naval powers of coercion; and oceanic protected areas have had remarkably little effect – the Great Barrier Reef, a Marine Park since 1975, is a striking example.

Fruits of the cyclone (that is to say, the eye of the storm, and introduced by flooding of our author's childhood home in Emilia-Romagna in 2024) focuses on institutions that have evolved to manage the environment. Over centuries, local and national institutions evolved to serve the social and physical infrastructures that insulate us from storms, floods and droughts; but the climate in which our societies and infrastructure evolved no longer exists. Neither structure is any longer fit for purpose– particularly for dealing with global issues.

The nature of nature, assesses the third building block of the environmental republic – its *purpose*. It turns out that the nature that most people have in mind and are prepared to pay for is not actually a property of the environment. It is relative to our desires: a mix of fantasy, functionality and social

values. What we mean by nature is *us:* the nature of society, which is not the same thing as Earth's carbon, water and nutrient cycles.

Everything in the environment has both function and place: we expect our environment to produce food, host biodiversity, support our infrastructure, be our home – safe from the destructive power of wind and water, *e.g.*, we want our coastline to be stable so we can build those beachfront properties and not watch them wash away. Whatever purpose we decide to give our republic, it ought to help us sort through all those expectations and make consistent, enduring choices.

Emergent voices. The idea of home is anchored in where we live but distance dims the detail. This disconnect makes it hard to voice when the environment is a matter of global commons: the ocean, the atmosphere. Somehow, voice must bring place with it – reflect its part in our life – which requires constitutional arrangements. Pastoral nomads could express their voice over great distances by movement, back and forth. In sedentary societies, democracies incorporate geography by dividing suffrage into constituencies and this is repeated in local government and civil society organizations. But the rules-based international architecture, that represented our collective interests since the Second World War, is being dismantled; human rights are deteriorating across the world; global public health has not recovered from the COVID pandemic … We are not doing well but, in the long view, managing our home together has been the big challenge of human history and an engaged community has always been its main protagonist – and only answer.

The rules of engagement have to balance the rights of the individual with collective purpose. In common law countries, legislators are *representatives* of their constituents: voice protecting the individual from coercion by the state. By contrast, under civil or Roman law, legislators are *deputies*, imposing the collective purpose; private interests always yield when the republic speaks by its law. Negotiating private interests is complicated because individuals have different experiences of the same reality over large scales. Negotiating common purpose generally relies on a geographic division of power in areas or regions of the political community.

Republican institutions tackles their role in linking people and place, in particular when action is needed beyond a local scale, where strategic adaptability may need to challenge some long-held ideas about property rights and the role of the state.

Rousseau reckoned: 'The first man who, having enclosed a piece of ground, bethought himself of saying "This is mine" and found people simple enough to believe him, was the real founder of civil society' [4]. Much earlier, Cicero argued: 'the chief preoccupation of the state-administrator must be to ensure that the individual keeps what is his [5].' Private property has been thought of as a marker of liberty ever since. No less fundamentally, Adam Smith's 'invisible hand' [6], more

recently wedded to individual responsibility [7] has been credited with an efficacy that can never be delivered by purposeful collective action.

Balancing private and public ownership of the bundle of rights associated with land is a crucial issue. In a world where most of the environment is in private ownership and that ownership is considered inseparable from self-determination, the state, representing collective action, needs to intervene in issues beyond the local scale. Our author advances two ways of doing this. One: the corporation-like public entity, *e.g.*, F.D. Roosevelt's Tennessee Valley Authority, a technocracy subordinated to the oversight of the people living in the catchment. Another: a national health service that relies on a common knowledge of what health is; a robust epidemiology – a causal theory of things that bring about public health outcomes, be they viruses or medicines; and a trusted system of responsibilities, for instance that a community has the right to protect itself against an epidemic. In these dimensions, environmental science has a lot of ground to make up.

Purpose as development: What, then, is the purpose of Boccaletti's proposed republic? Most people will settle for development: [8] but that demands growth. Mrs Bruntland's *sustainable development* [8] was an earlier attempt to square the circle. Our author considers the astounding modern development of China and the fate of assorted post-colonial republics to argue that, hidden in the problems of growth and its impact on the environment is a failure of political enrolment: systems incapable of corralling disparate voices to pursue a common purpose – without which, regime survival trumps any other concern.

Autocratic China, while lifting half a billion people out of abject poverty and becoming the undisputed leader in renewable energy and electric vehicles, and anyone's equal in science and engineering, has made the environment a central part of its constitution. It declares itself an *ecological civilization.* At the same time, it is the fastest builder of coal-fired power plants and the world leader in emissions. And what of the three quarters of mankind inhabiting the Global South by 2050? Planetary boundaries and lack of capital constrain consumption at the levels of consumption enjoyed by rich countries.

Our author denies biophysical constraints and focuses instead on legitimacy – liberty in the sense of self-determination in a place we call home [9] and the conditions that we might create there if we choose the quality of development rather gross consumption, as advocated by The *World Inequality Report 2026* [10] although the environmental failures that threaten our future, that destroy ecosystems, are not the product of economic inequality. Inequality is simply another failure with the same underlying cause: inability to ensure that people are the authors of their own lives and communities.

We, the people: Whom we mean by *we* matters. Our author's *we* is Europe and he springs it upon us as his proto-environmental republic. There is the unfinished business of European integration, the first step of which, in 1949, was a river basin authority along the lines of the Tennessee Valley Authority to govern the industrial production of the Ruhr. In view of the dismemberment of the global liberal order, there is a lot hanging on European integration.

At present, what holds Europe together are the four freedoms of movement in its single market: goods, services, labour and capital. A political purpose feels distant from the concerns of everyman but it need not be. Environment could be the missing link: 'If environmental phenomena become first-order preoccupations, as they are bound to, institutions will need to shift from the primacy of cultural affinity to that of environmental function' – that is to say, a green and pleasant land. Net primary productivity is no bad proxy for the health of the environment and it is worth a thought that, although most of the miniscule EU federal budget has been spent on an unashamedly social Common Agricultural Policy, satellite measurements of net primary productivity since 1981 [11] show that, considered as a single country, the European Union leads the world with a gain of 300MtC over 41 years[1], with no member state returning a loss.

Epilogue: Our author began with a personal reflection on the failure of scientific diagnosis to propel sustained environmental action. Returning to this theme, he concludes that reliance on science is a dereliction of political responsibility and delegation to a bureaucracy too fragile to withstand demagogues and tribalism. Far from sharing Plato's enthusiasm for philosopher kings, particularly the self-appointed variety, he argues for a civic pact through which people legitimately manage their geography and their lives together by negotiation: talking with each other, face-to-face and free from domination.

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dentsinengland@hotmail.com

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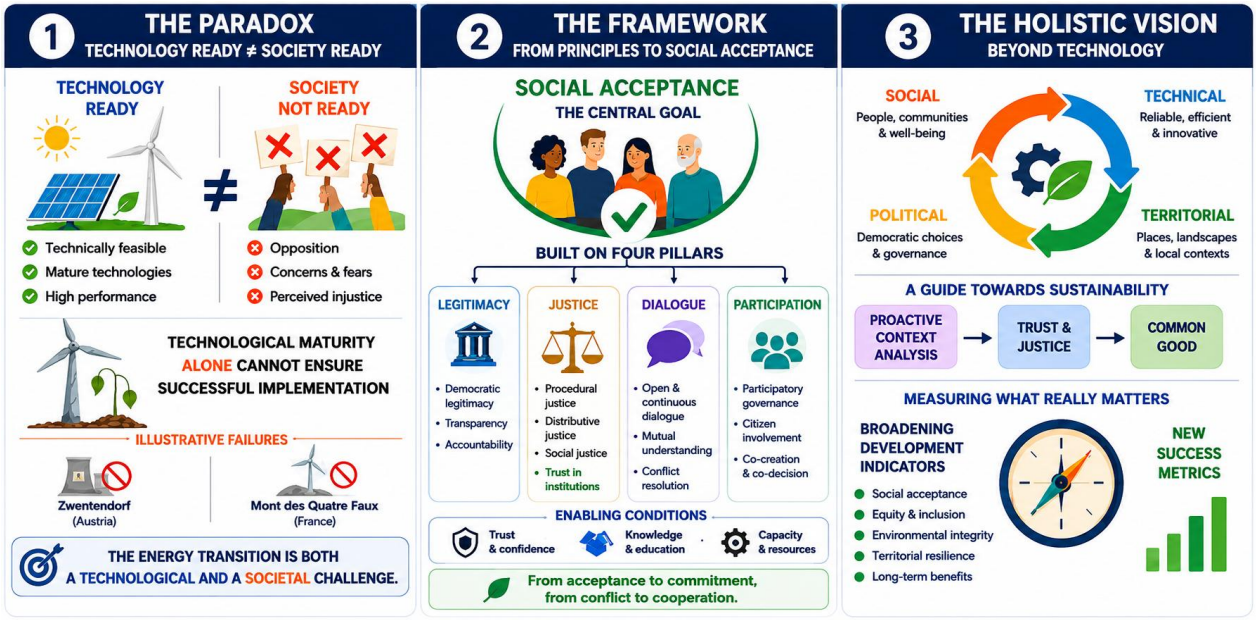
BOOK REVIEW

The Social Acceptance of Renewable Energy Projects, edited by Sébastien Bourdin. Cheltenham, UK: Edward Elgar Publishing, 2026. 364 pp. Hardback. ISBN 978-1-03534-874-9. eISBN 978-1-03534-875-6. DOI: 10.4337/9781035348756



One may spend many years designing a renewable energy production technology, advancing through the Technology Readiness Level (TRL) scale to a very advanced stage, and demonstrating that it is technically ready to be deployed, only for it never to move beyond the experimental stage (i.e., the Zwentendorf nuclear power plant in Austria or the Mont des Quatre Faux wind farm project in France) [1,2]. And this is not because it is ineffective, but because the most important thing has not yet been done: preparing the ground, giving equal importance to social maturity, and building acceptance (pp. xii–xv; 2–28). It is precisely this question that the volume edited by Sébastien Bourdin addresses.

This subject is particularly sensitive, because from a distance renewable energies appear to carry a very positive message, promising to provide all the power we need from the wind, the sun, water, or biomass!

We all wish to accelerate decarbonization, combat climate change, and achieve the energy transition. At the same time, we would prefer the wind turbine to be installed far from where we live, for the landscape to which we are attached not to be altered or saturated, and for no territorial injustice to be created (pp. 196–329). It is rather like saying, *"You can't have your cake and eat it too."* We therefore face a complex paradox, which can only be resolved through understanding the perceptions of opponents, an appropriate scientific approach, an integrated vision, an ecosystem of committed stakeholders, and a constant search for balance between interests that may sometimes diverge.

The Social Acceptance of Renewable Energy Projects demonstrates the extent to which the energy transition is as much a societal challenge as it is a technological one. Through this volume, Sébastien Bourdin first teaches us to understand the democratic legitimacy of an energy project (pp. 104–140), then to identify the factors that favour or hinder it (pp. 29–49), teaches us to analyse the conflicts generated by such investments (pp. 196–329), shows us how to mobilize the tools that strengthen public support (pp. 104–195), and finally to conceive the energy transition as a transformation that is at once technical, territorial, social, and political (pp. xii–xv; 196–329). None of this can be improvised.

This book does not merely explain why certain projects fail; it guides the reader towards understanding that the ultimate objective is not to obtain obedience. Instead, the energy transition is a process with inputs and outputs that must be prepared according to the context through a proactive approach. It provides the necessary guidance to help build and preserve the social acceptance of energy transition projects. A sustainable society rests not only on coercion, but also on trust, dialogue, perceived justice (pp. 29–49; 104–140), and the feeling of participating in a decision directed towards the common good. And it is this that truly determines the long-term success of public health policies.

The first chapter presents the complete interpretative framework and the terminological framework needed to understand what follows. We are introduced to the principal concepts that recur throughout the book: social acceptance, governance, trust in institutions, stakeholder participation, social justice, procedural justice (the way in which decisions are made), distributive justice (the sharing of benefits and constraints), risk perception, attachment to place, the saturation of familiar landscapes, power relations, positive incentives, citizen participation (pp. 104–195), as well as the different types of technologies according to their degree of integration into society. In short, the author provides us with all the keys needed to speak the same language!

On the other hand, I would also have liked to see the authors incorporate the concepts of *intergenerational justice*, *democratic sustainability*, and even revisit the notion of *clean energy*. For certain forms of energy described as "clean" ought to be excluded from this category. An energy source is not "clean" simply because it emits little CO_2. The impact on the climate should not be the only element taken into consideration; the impact on human health, the environment, biodiversity, and the very long-term consequences should also be included. Some questions likewise remain unanswered: when we finance these investments through borrowing, do we have the right to place part of the costs and risks on future generations? What duties do we owe to people who have not yet been born?

Once these prerequisites are recognised, the book's logic is clear. It first explains that social acceptance depends largely on perceptions, values, representations, and on psychological, cultural, and territorial factors. These elements shape the way in which citizens perceive an energy project.

What is discussed next is probably one of the book's major contributions. Support cannot be imposed; it has to be built. Sébastien Bourdin therefore explains how it can be progressively constructed through participatory governance, genuine citizen involvement, procedures perceived as fair, an equitable distribution of benefits and constraints, as well as continuous dialogue between all stakeholders.

Controversies and conflicts can be managed, and the authors provide numerous examples towards the end of the book, focusing on wind energy, hydrogen, geothermal energy, and value sharing. They analyse the mechanisms that lead to public opposition, phenomena such as NIMBY (pp. 298–312), and they present methods for assessing, anticipating, and strengthening social acceptance before conflicts compromise the deployment of projects (pp. 313–329).

It would be inaccurate to say that social acceptance always has the power to block a project. Several projects have been authorized and implemented despite limited citizen participation or strong social opposition. In a number of cases, the decision is taken mainly by the public authorities (i.e., the Flamanville nuclear power plant in France, as well as the Bure nuclear waste storage project), or social acceptance itself constitutes an objective. Nevertheless, it can be regarded as a risk factor for project governance (pp. 104–329), but also as one of the most important conditions for their legitimacy, stability, and long-term sustainability (pp. 104–140). Plainly stated, society must willingly accept solutions proposed in line with the Sustainable Development Goals.

These concepts developed by Sébastien Bourdin are transversal and applicable to many ecological transition policies, such as the ban on plastic bags [3]. In this case, the authorities may act very

quickly without questioning social acceptance. But, it remains legitimate to distinguish between two situations that the book sometimes tends to group together:

1. **Strategic infrastructures**, such as electricity networks, telecommunications, certain transport infrastructures or nuclear power. States may consider that these fall within the national interest and decide to implement them even in the face of opposition.
2. **Projects with a strong territorial impact**, where several options are possible (the siting of a wind farm, the location of a solar power plant, the choice of the route for an electricity transmission line, etc.). In these cases, citizen participation may serve to improve the project, select a better location, or distribute the benefits more fairly.

I place myself once again in the position of an observer within society. It is sometimes perceived that participatory procedures are selective, slow, bureaucratic, or even mobilized strategically according to the interests at stake, sometimes to demonstrate a commitment to democratic principles, and at other times to slow down the implementation of a project. I therefore leave myself with one question: when social debate is implemented, does it always represent the sincere expression of a democratic principle, or can it sometimes become an instrument mobilized according to the circumstances to block or unblock, slow down or accelerate, impose or legitimize certain decisions? Is it always a democratic end in itself, or can it sometimes become a strategic instrument of governance?

Finally, I find this book so stimulating because it convinces us of the need to broaden our vision of development indicators. The development of a society should not be measured solely by the conventional indicators with which we are familiar (i.e., GDP, HDI...). Certain additional indicators should be incorporated: social acceptance appears, *par excellence*, to be the necessary barometer for measuring commitment to democracy, and it is in this way that we will be able to define our position:

Are we those actors of governance who criticize behaviour while advancing in opposition to public benefit, to democracy, and to sustainability? Or are we those actors who seek to understand its true roots, take societal issues into consideration, and believe that the ground must first be properly prepared, and that social dialogue, ethics, and good faith are indispensable?

This book is particularly valuable for all stakeholders and decision-makers, but also for the ordinary citizen, whether living in a city or in the countryside, in the Rif or on the plains, in the desert or at the heart of the metropolises. It raises awareness that everyone has rights, but also duties in the face of the challenges of the energy transition.

Far more than a book devoted to renewable energy, this volume is exceptionally stimulating because it encourages us to reflect upon several issues facing our society. This book helps us to understand the mechanisms that lead to the success or failure of many projects, mechanisms to which too little attention is often paid and which should frequently be considered upstream of the implementation process. It also reminds us that social acceptance gives full meaning to the saying, *"It is better to do it properly the first time."* In reality, conflicts surrounding renewable energy are often as much conflicts of governance as they are conflicts of social justice.

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nadia.boutaleb@fstm.ac.ma

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